Robotic Assisted Design:
A study of key human factors influencing team fluency in human-robot collaborative design processes

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SUMMARY

Architecture is going through a new phase of consolidation after a paradigm shift on how architecture is conceived and produced. It includes an increase in interdisciplinary approaches, a deep relationship between architecture and technology, a new era of trial and error – of prototyping in theory and in practice – and, most importantly, a change in the relationship between thinking and doing. Work within architecture research laboratories has focused on connecting parametric models with robotic manufacturing tools and materials that allow the production of many different, customised parts. This idea stems from viewing robots as precisely controlled machines for fabrication and has led to the current scenario of relatively unchanged models of human–machine interaction and design processes. However, evolution in the field of human–robot collaboration suggests that the implementation of technological change should not be viewed simply as an engineering problem. It is crucial to understand the human factors that are needed for the successful integration and implementation of new technologies.

This dissertation aims to understand key human factors that influence the development of symbiotic agencies in robotic-assisted design. It explores the relationship between digital architectural design and its materialisation through a collaborative process between designer manipulation, phase-changing materials and robotic fabrication. In this context robotic technology is utilised as an 'amplifier' in the design process to realise geometries and architectural visions through iterative feedback loops. The robotic environment enables synchronised analogue and digital modelling through robotic agency within a dialogic design process between materials, computational hardware, software tools and the designer. Experiments, case studies and a controlled user study have been developed to test this workflow and evaluate the theoretical framework of key human elements that need to be considered for the successful implementation of human–robot collaboration in the architectural design process.

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Journal Papers

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Nahmad Vazquez A., and Jabi, W. (2017). *RAF: A Framework for symbiotic agencies in Robotic – Aided Fabrication.* Charette journal of the association of architectural educators, Volume 4, Number 1, Spring 2017 pp. 58-73 http://ingentaconnect.com/contentone/arched/char/2017/00000004/00000001/art00006

Nahmad Vazquez A., and Jabi, W. (2017). *Pop-Up Concrete Constructions: Forming Fabric Reinforced Concrete Sheets.* International Journal of Computational Methods and Experimental Measurements, Wessex Institute of Technology. Volume 5, Issue 4, 2017, pp. 451 – 463. ISSN: 2046-0546 (paper format), ISSN: 2046-0554 (online), http://www.witpress.com/journals DOI: 10.2495/CMEM-V5-N4-451-463

Nahmad Vazquez A., and Jabi, W. (2015). *A collaborative approach to digital fabrication: A case study for the design and production of concrete pop-up structures.* International Journal of Architectural Computing, volume 13 issue 2, June 2015. https://journals.sagepub.com/doi/pdf/10.1260/1478-0771.13.2.195

Conference Papers

Nahmad Vazquez A., and Jabi, W. (2016). *RAF | A Framework for symbiotic agencies in Robotic – Aided Fabrication*. In P. Weber, ed. Proceedings of the International Peer-reviewed Conference on “Research Based Education”. The Bartlett School of Architecture, UCL, pp. 130-149. https://issuu.com/bartlettarchucl/docs/aae16_publication_volume1

Nahmad Vazquez, A., Jabi, W. (2015). *Pop-Up concrete: Digital and Physical materiality.* TxA Emerging Design + Technology Conference Proceedings held during the Texas Society of Architects 76th Annual Convention and Design Expo in Dallas, Texas. Eds. by Kory Bieg. pp 9-17

ABBREVIATIONS

ANT - Actor Network Theory

CAD - Computer Aided Design

HCC - Human Computer Collaboration

HCI- Human Computer Interaction

HIRC - Human Industrial Robot Collaboration. Refers to the specific cases when the collaboration is with an industrial robot arm.

HRC - Human Robot Collaboration

HRI - Human Robot Interaction

HRT - Human Robot Team

PAR - Participatory Action Research

RAD - Robotic Aided Design

WSA - Welsh School of Architecture at Cardiff University

Chapter 0 INTRODUCTION

0.1 Summary of the Research Problem

In the last two decades industrial robotic arms have moved from specialist environments and have started to colonise other locations. As robots become ubiquitous in the field of architecture (Gramazio and Kohler 2008; Gramazio et al. 2014), it has become crucial to think about the interactions that designers have with them and the design processes that can make the most of robot characteristics and human skills. Furthermore, a crucial question to enable the broader integration of robots into the field is how the use of robots in architecture may accommodate the designer-in-the-loop as a domain expert and not a robotics expert. Thus far, studies on robots in architecture have mostly been focused on using robots for fabrication and understanding their implications, advantages and limitations, and concentrating on the technicalities of the technology. Few studies have been conducted to understand how robots have altered designers' workflows and their relationship with the materials and the physical world.

This research aims to determine the relationship between the designer and the robot with the goal of a better understanding of how designers relate to the machine during their architectural design process and what specific characteristics are required from the robot, the design task, and the designer to enable these interactions. It aims to see robotics in architecture as more than a mere technical and material innovation tool. Through iterative feedback mechanisms and observation of the relations created between the designer and the robot, the research speculates how a deeper collaboration that acknowledges the *"potential otherness"* (Picon 2004) of these tools, through a learning-by-design method, could lead to the creation of new choreographies for architectural design. The emphasis throughout the research is on the connections and relationships facilitated by the digital software through the physical manipulator (the robot) between design intent, computation logic and physical material.

This dissertation looks at the field of human–robot collaboration (HRC) and reviews studies on human–robot collaboration in industry, which refer to industrial robot arms, to dissect the key human elements that enable such collaborations. This dissertation proposes and uses the term **HIRC** to refer to human–industrial robot collaboration. First, to differentiate it from other kinds of robot collaborations and secondly because a lot of parameters relevant to industrial robots, due to their characteristics, would not be important for designers collaborating with other types of robots (e.g. drone 3D printing).

HRC is a multidimensional context-dependent construct; this makes it essential to understand how team fluency develops when designers who are non-expert robot users, interact with industrial robots. HIRC during the early stages of a design process can enhance creativity and exploration, as the weakness of one partner can be complemented by the strengths of the other. However, the integration of humans and robots within the same workspace remains a challenge for the human teammates. For technologies entering a new field to be fully accepted, a considerable amount of attention needs to be placed on the human factors that will enable the acceptance of such technologies, and inattention to the human element can be detrimental to the technology. In order for robots to be supported by designers beyond specialised courses and the early enthusiasts, designer's concerns and needs must be considered; otherwise, the discipline is risking failure in introducing robot technologies at a larger scale into the design-thinking process of architectural designers.

This research outlines a theory of HIRC in architectural design and proposes a theoretical framework and its evaluation methodology for the key human factors relevant to team fluency in a human–robot design team. The themes and sub-themes of the design collaborative framework are then tested on non-expert robot user designers. Researchers in the field of HRC have developed and set basic metrics to evaluate HRC in cases when the robot is an industrial arm. However, their scope is limited and with a very specific focus on humans and industrial robot arms accomplishing clearly specified, predefined tasks, rather than on creative, unpredictable, and intellectually intense tasks, such as the design activity. A crucial difference between both is that traditionally, when an engineer is setting a robotic cell, he is trying to solve a very specific problem. On the other hand, when a designer is trying to set a robotic cell, it is usually in a quest to find the right questions rather than the right solutions in what can be called a process of creative enquiry. The paradigm shift is from using robots to find the right answers to using robots in order to find the right questions. A framework to evaluate HIRC for intellectual, creative tasks positioning the robot at the centre of the design task as a creative partner has not been developed.

0.2 Research Aims

The objective of this dissertation is to look at HIRC in the design task from a human perspective that allows the identification of the key human factors (factors influencing the human), robot factors and design worfklow (factors influencing the design task) that need to be considered for team fluency in an HIRC design process.

A design process was designed and described on the basis of sensor feedback and phase-changing material formations. The design worfklow is based not only on empirical data and practical experience but also on a complete view of the design activity, and some prediction and explanation. The form-finding process, robotic performance, and structure of the phase-changing material are first simulated digitally and then physically performed between the human and the robot. The robot is positioned during the initial form-finding phase of the design process. It can then, enabled by a vision sensor, become a partner providing input and collaborate by giving information back to the designer throughout the phase-changing process of the material. In the proposed workflow, the results are not predefined but their potential delineated and then explored through the HIRC. One important consideration for this research is that designers are not playing for an unexpected creation to emerge out of tinkering with the robot; they go through a rigorous design and iteration process, which defines the solution design space from which the final results emerge as a product of the HIRC. This position this research in-between offline robotic programming and live robotic programming which can be limited by the complexity of the task. The dissertation aims to unpack the social implications of explicit interactions across design, information, materials, designers, and machines. In this new context, it becomes crucial to study how designers feel about working with robots and identify aspects of the design task and behaviour of the robot that can improve the success of a human–robot team (HRT). The research identified and analysed key team fluency elements for successful cooperation between humans and robots, such as trust, reliance, and robustness. With the concept of HIRC design being embraced further, it aims through case studies to quantitatively and qualitatively explore the human factors in depth to provide insights that enable the successful acceptance and use of industrial robots as collaborative design partners, beyond sophisticated fabrication machines.

Through the analysis of the case studies, this research aims to discover how HRT fluency emerges in an architectural design scenario and as a function of the relationships between the different agencies in the design process. Suggestions about when and why designers start to cede agency to the robot are discovered, and preliminary hints about the necessary protocols for enabling the interaction between the agents start to emerge

0.3 Hypothesis

Research on HRC has been mostly focused on assistance, health, or military robots. Industrial robots have been designed to exist behind security cells, and research on HRC when the robot is an industrial robot arm remains a nascent camp in the industry (Charalambous 2014). Furthermore, to the best of the researcher's knowledge, thus far, the relationship between robot arms and architectural designers has not been investigated. The characteristics of a robot arm, such as accuracy, precision, and its link to the digital environment, that make it ideal for manufacturing also make it a partner that can complement and augment the designer, particularly as the design genesis becomes increasingly digital. However, the design process is an exploratory process, whereas manufacturing is looking for precise results. Glitches that can be immediately categorised as wrong in a manufacturing task can be appreciated and lead to new, unexpected exploration avenues for a designer.

This research hypothesises that for robotics to permeate into architectural discourse at a deeper level than that of highly sophisticated fabrication tools, robots need to become environments that augment the designer and transform the creative process by enabling new dialogues and collaborations. Understanding the human, material and robotic agencies and their interactions is fundamental to shape these new robot-mediated design environments, moving the robot from being a final fabrication tool to a facilitator of a holistic environment that integrates the different material, human, and digital agencies in which design develops, encourages novel ways of thinking and non-hierarchical design modes. It brings techniques and technological knowledge into a deeper relationship with the narratives of the discipline of architecture by augmenting the relationship between the digital model, the designer, and the physical object.

0.4 Objectives and Contributions

The use of computers and hence robots, which are computers able to perform in the physical world (Corke 2015), by humans to successfully achieve an interesting task is a highly complex phenomenon. It involves *"the interaction of human intelligence, motivation and skilled performance, complex enough in their own right, with another information processing system of lower, but still substantial complexity"* (Wolf et al. 1989, p.265). Predicting what these combined complexities will do is very difficult or impossible.

0.4.1 Objectives

The HIRC design process was dissected into the main elements that can influence its development and successful implementation. Based on this, a set of traits was identified and evaluated to obtain a comprehensive idea of important qualities in a collaborator for designers and the enablers and inhibitors for successful HIRC in design processes. The following three main objectives were set to achieve this:

First: Developing a design workflow that merges human, robot, and material agencies during the process of creation. The design workflow is based on exploiting the strengths of the human and of the robot to enable a collaboration that is beneficial and satisfactory. The design workflow should be relevant to the design methods and tools used by architectural designers. Finally, it should be suitable for use by architectural designers who have not previously participated in a specialised robot or digital fabrication-based programme.

Second: Identifying key human factors influential for the development of team fluency in HIRC in the design task. A literature review of the comparable research on HIRC was performed. Further, a theoretical framework for the key human factors promoting team fluency was developed.

Third: Exploring the key elements from the team fluency theoretical framework in the context of architectural design. The focus was to investigate whether the human factors identified in the literature were enablers, barriers, or irrelevant for HIRC in the design activity. This was achieved through exploratory case studies where the collaborative design workflow was implemented with non-expert robot user architectural designers. Results were evaluated to unfold the construct of HIRC team fluency during the design activity.

The completion of these objectives enables the research to meet its overall aims: 1) identifying and developing a framework of key human factors that are relevant for team fluency in HIRC during the design activity; 2) developing and testing a design workflow that allows a collaborative workflow between the designer and the robot; 3) evaluating the development of team fluency and identifying additional relevant human, robot and task factors that enable HIRC in design tasks for architectural designers who are not expert robot users.

0.4.2 Contribution

The history of evolution in the field of HRC suggests that the implementation of a technological change should not be viewed simply as an engineering problem. In the same way as merely rolling industrial robots onto the shop floor does not ensure acceptance and effective use, rolling robots into architectural institutions would not do so either. These intelligent systems will invariably alter the designer's role and workflow. Therefore, it has become crucial to understand the key human factors that need to be considered for the successful integration and implementation of robotic-aided design (RAD) in architectural design processes.

RAD is a digital-physical design method proposed and evaluated by this research, as a response to a rapidly changing architectural practice that increasingly relies on outputs that cannot be generated without the use of computers. It utilises the new opportunities generated by digital design and fabrication machines for design. Contemporary design education and practice needs to be based on digital design making and thinking rather than outmoded templates more appropriate for paper-based workflows (Oxman 2008). Robots when coupled with computers and digital design methods introduce *"associative and performance-based processes not available to the predigital era"* (Roudavski 2011, p.441). These methods change the conventional relationships of a 'unidirectional' design process and introduce the capabilities for 'multi-directional' material- and fabrication-informed augmented design processes (Ahlquist and Menges 2011).

Through the case study, a scenario of HIRC in architectural design was developed and evaluated against a set of human, robot, and task metrics from the literature. The main contributions of this research are as follows:

1. Identifying key human, task and robot factors that need to be addressed in HIRC design processes and the relationships between them;

2. Providing a framework, and its evaluation methodology, of key human factors relevant to the implementation of novel technologies in the design studio, particularly HIRC;

3. Providing an understanding of the above key factors and their influence on the development of team fluency in HIRC design processes; and

4. Their implementation and important characteristics that need to be considered during the development of RAD workflows.

Furthermore, the findings could provide suggestions for robotic manufacturers in the development of robot characteristics to support designers in collaborative tasks.

0.5 Theoretical Resources

The approach taken by this research is based on a 'post-human' view of the design activity. This allows it to focus on how things and people perform together, create relationships, influence each other, and organise in certain ways. Actor-Network Theory (ANT) and Participatory Action Research (PAR) are used as theoretical and methodological frameworks for this investigation.

ANT is a theory pioneered by Michael Callon and Bruno Latour which investigates social and technical aspects together as an actor-network of human and non-human elements (Latour 1999). It gives social and the technological elements equal value by treating them as inseparable; in fact, it argues that *"people and artefacts should be analysed with the same conceptual apparatus"* (Walsham 1997, p.467). ANT enables thinking about hybrids of people and technology and hence offers a way to investigate the issues and dilemmas for robot-augmented designers. In this context, the question is how actors become interconnected and perform as a product of their associations rather than of their individual characteristics (Dolwick 2009). ANT focuses on the relationships between agents or 'actants' rather than giving primacy to perception. The design process can be understood as a human abstraction, related to the human, or as a subjective component, an element within a wider assemblage of humans and machines. This second understanding of design as an assemblage does not separate the human actor from the other actors in the network, but considers all symmetrically.

The second method, PAR, advocates a plurality of methods to gain knowledge, mainly participation, experimentation backed by evidence-based reasoning, fact-finding, and learning (Tripp 2005). PAR was used during the implementation process where the researcher assumed an active role throughout the process that allowed refinement of the workflow cyclically and learning from direct experience with the experiments.

0.6 Organisation of the Dissertation

This thesis has been structured in the following order (Figure 0-1):

Part I positions the dissertation in the larger theoretical context and advocates the use of ANT as a framework to guide the development of the dissertation.

Chapter 2 presents a critical review of robotics, collaborative robotics, and the development and evolution of HRC. Chapter 3 focuses on the design process, its evolution, and the close relationship between architecture and technology (Steenson 2017), searching for areas of intersection between designers, materials, and technology. It advocates that the intersection of human abstraction, materials, and techniques can result in a variety of conditions offering new opportunities for the development of the design process and new roles for design and the designer. A description of the different agencies influencing the design process and their contributions is made before any relationships are formed. It then links the development of robots with the development of architecture and the clear relationships between tools, computing, and design.

Rather than reviewing and classifying all the experiments and the work going on currently regarding robotic uses in architecture, the first two chapters map the main issues linked to the development of robotics and the human−robot symbiosis in architecture. It is probably too early to decide how robotics will evolve to become an enduring design tool rather than a fabrication one, and how robots will morph the discipline as a whole. However, human problems caused by robotics in architecture can already be identified, and a framework of key human elements is proposed and developed for HIRC during the design process.

Chapter 4 discusses the development of a theoretical framework of key human factors relevant to team fluency in HIRC design tasks based on the literature review.

Part II starts with the work carried out to understand if the outlined human factors were relevant to the design process and whether they were enablers or barriers for successful HIRC.

Initial explorations were conducted with non-expert robot user designers carrying out a collaborative design task. Qualitative and quantitative data collection tools were tested through the development of the case study.

Chapters 6 presents and discusses the approach taken to investigate the human factors outlined in chapter 4 and refined through the exploratory case study discussed in chapter 5.

In chapter 7 a description of the research study, its design and application in detail is presented. The idea of "following the actors" provides the structure for the chapter as each actor is introduced in the order in which they came into contact with the design process.

In chapter 8 concepts and findings are presented in a practice and experience-based way. It measures the developed scale and questionnaires to evaluate team fluency and their validity for the design exercise.

Chapter 9 presents an overall summary of the results emerging from this research. The results and interpretations move beyond mere practice and practical considerations to the presentation of more theory-informed interpretations.

Chapter 10 gathers findings from chapters 8 and 9 to provide guidance on the human factors that should be considered when introducing robots as collaborators for designers, in the form of propositions, to enable the successful implementation of design HIRC teams. It discusses the limitations of the research and provides a theoretically guided interpretation of the results. It ends by addressing the overall aims of the dissertation and provides suggestions for future work.

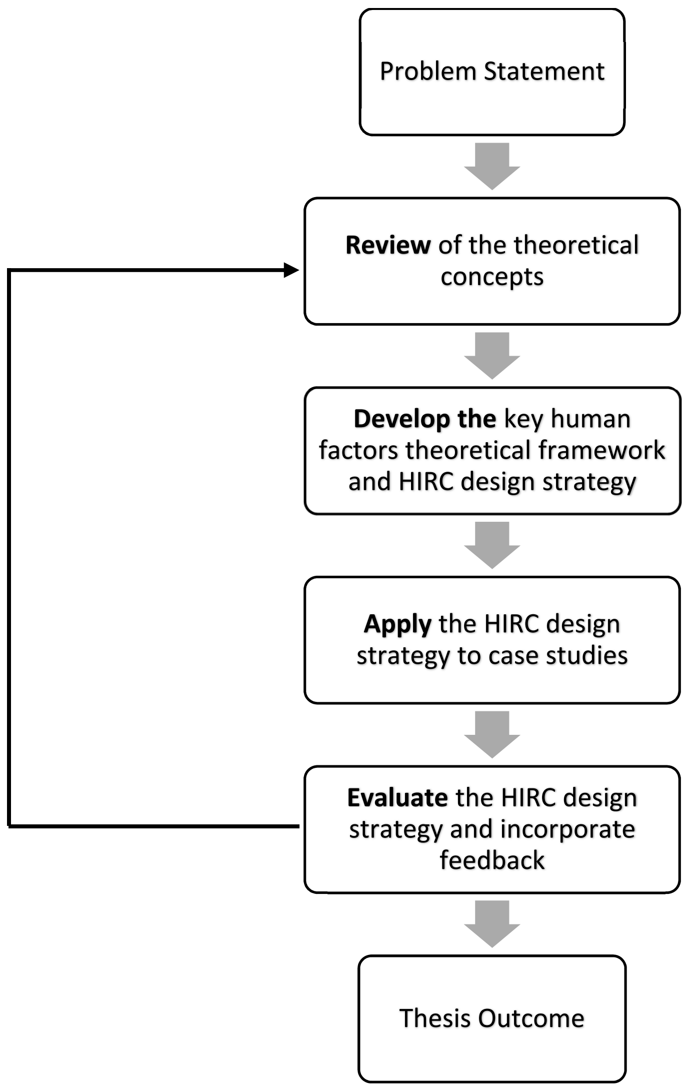

Figure 0-1 Map of the Dissertation

Chapter 1 THEORETICAL RESOURCES AND RESEARCH METHODOLOGY

1.1 Introduction

This chapter introduces the theoretical resources and research methodologies that serve as the lens for this dissertation. The study of HRC in design tasks relies on a diverse set of methodologies and philosophical frameworks. A purely scientific methodology based on the standards of human and design performance has been rejected, as its metrics and measurements are appropriate for situations where tasks can be broken down into specific computer and human tasks, which can then be measured in discrete and quantitative ways. The phenomenon that this thesis investigates is not easy to measure using the existing metric methods, as they are not suited for cases *"when the usage of new technology is discretionary rather than task performance in a controlled work setting"* (Lazar et al. 2010, p.5). Additionally, design is not a linear optimisation problem: quantitative measurements cannot determine the gain when the designer uses a robot versus when not, or the reasons behind the decision to use it.

The research advocates the use of a theory from science and technology studies, Actor-Network Theory (ANT), which accommodates personal relationships between human and non-human actors. This theory is different from humanist theories that currently pervade research in the area of human−technology interactions and which *"confine 'technological things' to the nonhuman side of a human/nonhuman binary relation"* (Shaw-Garlock 2010, p.1). Through its concepts and translations, ANT analyses heterogeneous networks that link materials, knowledge, humans, and technologies, focusing on the negotiations between these links. It considers the phenomenon of design to be a result of the relationships between the different agents and the complex networks that they create during their interactions.

During the implementation phase, a second method, Participatory Action Research (PAR), is used, which places emphasis on a collaborative partnership between the researcher and the participant committed to producing a result.

The case studies, data collection and data analysis were set up using a mixed methods research approach in which quantitative and qualitative methods are integrated into a single study with the aim of understanding the fabric of reality and producing a more inclusive and expansive understanding of the topic (Frels and Onwuegbuzie 2013). Finally, template analysis was used to summarise the themes arising from the data, to hierarchically organise these themes and to present the results.

The concepts of each of these frameworks and methodologies are examined and described in the following sections together with their application to the HIRC design exercise.

1.2 Actor-Network Theory

ANT is a research methodology developed in the late 1970s and the early 1980s by three independent scholars from the fields of science, technology, and sociology: Michael Callon, Bruno Latour, and John Law. Its main focus is the concept of 'actant', which exists in social networks. In ANT, the world is made up of complex networks of objects. Actants are the objects in the networks and can be human or non-human. All actants have equal value and agency and are equally important to the functioning of the network. Meaning arises from the relationships between the actants (Latour 1987, 2005; Callon 1990; Law 2007). ANT is concerned with *how* networks form and the meanings of these formations rather than with *why* they form. Law (2009) argues that ANT, as a methodological position, is a descriptive toolkit that sensitises the researcher to the messiness of materiality and its relations, and enables him or her to tell interesting stories about these relations and to make inferences from them. ANT can also be described as a 'material-semiotic' method. This means that it is concerned with mapping relations which are material (between things) and semiotic (between concepts) with many relations being both (Law and Hassard 1999). Law (2009, p.141) describes ANT as *"a disparate family of material-semiotic tools, sensibilities, and methods of analysis that treat everything in the social and natural worlds as a continuously generated effect of the webs of relations within which they are located. It assumes that nothing has reality or form outside the enactment of those relations".*

ANT is used as a theoretical framework in social studies of technology aiming to understand the way technological artefacts are constructed in society. Treating both people and technological artefacts symmetrically allows exposure of relationships and contexts which may be more difficult to detect using other approaches (Tatnall and Gilding 1999; Doolin and Lowe 2002). In the following section, a review of the fundamental concepts and techniques of ANT is presented along with how these ideas can support an effective frame for examining the human−robot−material relationships in the HIRC architectural design process.

1.2.1 Core Propositions and Principles of ANT

ANT as a research framework reframes the research object as a complex network of objects. The aim is to unveil what is linked together in these networks and let go any preconception of what constitutes an appropriate 'assemblage' (Latour 2005). It proposes a *symmetrical* view of human and non-human agencies, where neither is reduced to the other nor dismissed in relation to any other; they evolve and depend on the relations that they form with each other. The world in this context is made of a series of negotiations between forces of objects which have symmetric relationships. It cannot be cleanly divided anymore into distinct poles of 'human' and 'non-human' or 'reason' and 'force' (Latour 1993).

In the context of HIRC in architectural design processes, the network encompasses not only robots and designers but also physical materials, design ideas, end effectors, design software, communication protocols for robotic control and robot software, other technologies present in the configuration such as sensors, other designers in the design studio, and additional design features of the robot. Together, they form one design network. Through ANT, the aim is to understand how the network comes into existence and how it acts as a whole. In the following paragraphs, the relationships between the different actants in the network are described and referred to in the key terms of ANT.

Actants. One of the most frequently used terms in ANT together with 'actor'. It refers to the ability of non-human objects to act, whereas an actor is mostly a human actor (Latour 2005). Actors and actants are then all participants in the network (human or non-human), have a presence, and can make a difference to the network. The term actant is preferred over actor as it is more inclusive. In the design scenario, it is possible to distinguish the designer actant from the broader set of actants. The latter includes the robot, physical materials, end effectors, digital and physical tools, and even abstract ideas and design concepts (Aimee 2013), all of which have agency and are meshed into networks with the designers. Actants are real, not through nature but through their effects on the other entities (Harman 2009), and they are defined in terms of their relations. An actant cannot exist if it affects nothing at all.

Translation. Describes both the creation of links between actants (actor-networks) and the formation of order amongst them. Through a translation, the actors in the network associate and influence each other (Belliger and Krieger 2016). Translations are used to link heterogeneous materials, knowledge, emotions, agencies, bodies, and technologies (Latour 2005). They take place in real time at each stage of the process and are necessary to mediate between the various points in the network. In the design scenario, this means making the digital tools and robot behaviour understandable, transparent, and easy to apply for the end-user designer. For the robot, it would mean using stable physical and digital tools which minimise unexpected behaviours, design deviations and material damage.
Different types of translations can take place at different stages of the process with different effects on the actor-network as follows:

1) When an actor becomes more prominent and 'reassembles' the other actors to form a network around it. In this case, the other actors will assume the cause of the first one as their own (i.e. a team leader is a more prominent actor; the other actors (team members) assemble around it and assume the cause of the leader).

2) When less prominent actors become stronger (i.e. a student shifting the attention of the class to talk about video games).

3) When an actor takes a short-cut to solve his cause (i.e. hires someone with the knowledge

needed to solve the problem rather than acquiring this knowledge).

4) When actors associate but keep their own identity, similar to symbiotic processes in nature.

5) When actors become obligatory passage points for other actors (i.e. an actor becomes highly influential in a field and everyone else needs to cite him).

Tokens or Quasi-Objects. Successful interactions between the actors in an actor-network that get passed throughout the network are called tokens. As tokens get increasingly passed through the network, they get punctualised (see below) and normalised until eventually they get taken for granted. When tokens are not frequently transmitted through the network or when errors occur during their transmission, punctualisation is decreased and problems can occur in the actor-network. This means that successful interactions between designers and the robot would be transmitted to the other actors in the network and lead to the improvement of the physical and digital tools, consequently benefiting the designer.

Punctualisation. When actors combine into a single actor, punctualisation occurs, which also denotes a combination of actants which become one actant inside a larger network. The concept of punctualisation is related to black boxes. A black box is an object which is perceived as a single entity although it consists of various components. The robot arm can be considered a black box even when it is composed of numerous components. Problems with any part of the robot (i.e. software, end effector, sensor, and processing operations) may be considered a problem with the robot as a single entity. In the context of this dissertation, each actant from the black box robot might trigger different reactions. Thus, these actants should be analysed as single actants within the actor-network. Black boxes can be opened at any point to reveal the components that gave rise to it (Latour 1999). This generally occurs in moments of crisis or when the normal functioning of the actor-network is affected. In this case, de-punctualisation occurs, and the punctualised actant or black box and all the elements inside the box become visible. What was perceived simply as a box is now decomposed into its parts (Latour 1999).

Heterogeneous Networks. Networks in ANT include 'social' and 'technological' parts. A heterogeneous network is that in which the interests of the actants are aligned (Cressman 2009). In the case of human actors, interviewing them is a way to understand their interests. With respect to technological actants, the observation of the technology and interviewing its users as well as analysing the related documentation can be ways of understanding them. In the collaborative design process, the designers' points of view are assessed through interviews complemented with quantitative questionnaires and observations of the interactions between the physical and digital actants.

Obligatory Passage Point (OPP). Are critical incidents in which the survival of the actor-network is in danger (Callon 1984). In an OPP the elements need to transform their actions and adjust their interactions and converge around the issue at play in order for the network to exist. An example of an OPP could be a critical incident that leads to the rethinking of the technical functions of the robot.

Finally, ANT accounts for time as a variable in which the network develops. Using ANT, the researcher can focus on the particular roles that the objects play as their network develops, stabilises (if it does), is maintained, and eventually disintegrates (Brown and Capdevila 1999). The network that was formed between elements, the materials, and the designer might not need to exist after the design exercise is done. Alternatively, it can evolve if the designer keeps engaging with robots, then, the feelings and agencies of each would evolve.

1.2.2 Feasibility of ANT for this Research Exploration

The design process can be understood as a human abstraction, related to the human, or as a subjective component, an element within a wider assemblage of humans and machines. This latter understanding of design as an assemblage does not separate the human actor from the other actors in the network, but they are all understood symmetrically. Carpo (2011) describes architectural design as an informational operation in which the underlying processes are defined by specific technologies. Designers are actors whose qualities are a result of the alliances with the current set of actors in their design process, education, and relations. When they start using new tools and technologies, new relations start to unroll which will change them and move them into a different state. A network tracing approach that addresses the otherness of each element is useful for understanding and revealing the interactions and connections between the different design actants. Using ANT, the technological context is closely related to the social context. The social consequences of technologies are a result of the iterative processes of interpretation and negotiation between the social and the technical. A technology change is never independent of the particularities of its social context (Callon 1984; Latour 1993).

ANT, in the context of this dissertation, is focused on the analysis of the collaborative design network. It aims to understand how as the network unfolds, the perspectives of the designers (actors) transforms. Technology and society are mutually determinant: people shape technology, and technology shapes human behaviour (Callon and Latour 1992). ANT provides a common language to describe and compare both and the networks that they assemble. Through ANT, the interactions and the dependencies amongst the actants can be mapped and described in order to understand the relationships and influences between them and to the design activity.

1.2.3 Acknowledging Changes and Limitations of ANT

The symmetry between human and non-human actors has been identified as a limitation of ANT (Pickering 1995). For Latour, both work together in agreement towards shared goals whereas Pickering (1995) notes that humans and non-humans cannot be the same, unless reduced to semiotic constructs. While humans have intentions and goals, non-humans do not. Additionally, human intentions and goals are conditioned by the specific time and culture in which they develop. Humans and non-humans are not two agencies but a continuous *"dance of agency"* in which humans find resistance from the material world and change their models on the basis of these findings. Material and human agencies continuously intertwine and are reciprocally defined in an *"emergently intertwined delineation and reconfiguration of machinic captures and human intentions, practices, and so on"* (Pickering 1995, p.23).
Another limitation comes from the definition of the different objects. The more we define an

object by its relations, the more we strip it from an autonomous reality, which will result in a universe devoid of any specific realities. This is similar to how relational philosophies from the Socratic era defined the world. Recent philosophers of the virtual working around the works of Deleuze, such as DeLanda and Simondon, have tried to position 'pre-individual' zones to prevent the world from being a homogeneous mass. DeLanda proposes a *"continuous, yet heterogeneous space"* (2013, p.27) with the aim of having a heterogeneous world, but which is divided into individuals. Actants in ANT are fully defined individuals from the beginning. They are not blended together in continuous but heterogeneous wholes; they are initially independent from each other. This allows for a less radical relationism, as actors cannot fully dissolve into a system of relations (Harman 2009).

Finally, ANT has been criticised as not being enough of a scientific method, not leading to objective insights, and not offering insights on how to improve the status quo (Boltanski and Chiapello 2018).

1.2.4. ANT as a Methodology

Unlike conventional research approaches, there is a lack of detail, description, or direction around methods for ANT investigations. It is common to find rich accounts of fieldwork and elaborate descriptions of the scenes but how were they collected or how are they connected is not explicit. Latour (1996) hints at the connection structure in the detective story of his experimental book '*Aramis*'. The clearest explication of the structure for the research inquiry can be found in '*Reassembling the Social*' (Latour 2005). In there, he lists *"the different notebooks one should keep–manual or digital –it no longer matters much"* (Latour 2005, p.134) to enable and support the research exercise

> *A first notebook should be reserved as a log of the inquiry itself.*
>
> *A second notebook should be kept for gathering information in such a way that it is possible simultaneously to keep all the items in a chronological order and to dispatch them into categories, which will evolve later into more refined subfiles.*

A third notebook should be kept for writing trials.

A fourth type of notebook should be carefully kept to register the effects of the written account on the actors whose world has been either deployed or unified (Latour 2005, p.134,135).

ANT is descriptive in its aim to tell stories about *how* relations assemble or do not (Law 2009). The descriptive notebooks become the guiding tool for the enquiry process. Latour (2005, p.135) describes that:

It might be disappointing for the reader to realize that the grand questions of group formation, agency, metaphysics, and ontology that I have reviewed so far have to be tackled with no more grandiose resources than tiny notebooks to be kept during the fully artificial procedure of fieldwork and enquiries.

For Latour, social explanations are superfluous additions that dissimulate what has been said rather than revealing the forces behind it (Latour 2005). Latour's concern with descriptions is reflected in one of his key principles: the intent of the analysis. He is clear in emphasising the task of the researcher as one concerned with describing how networks come together and how they stabilise or fall apart in the process. For him, *"if your description needs an explanation, it's not a good description, that's all"* (Latour 2005, p.147).=

1.3 Participatory Action Research (PAR)

Participatory design methods are those which involve users from the early stage of the design process. Action research aims to create a common background of understanding committed to producing a result. PAR emphasises a collaborative partnership between the researcher and the participant with the common objective of completing a design task rather than a one-sided relationship of the subject and the experimenter. In action research, the process of making and designing an artefact constitutes the methodology (Seago and Dunne 1999). This scenario is meaningful for design tasks which aim to produce systems that are usable and enjoyable for all the parties involved (Wolf et al. 1989). During the conceptual stage and the set-up of the research task, the HIRC design framework was constantly evaluated and adapted according to the participants' reactions through the different stages of the process.

Tripp (2005) considers action research a type of action inquiry that allows the improvement of practice as the researcher has an active role during the investigation process:

> *Action inquiry is a generic term for any process that follows a cycle in which one improves practice by systematically oscillating between taking action in the field of practice, and inquiring into it. One plans, implements, describes and evaluates an improving change to one's practice, learning more about both the practice and action inquiry in the process* (Tripp 2005, pp.445–446).

An important aspect of PAR is the documentation of the different steps through field notes, diagrams, photographs, and videos. This is consistent with the descriptive nature of the research enquiry advocated by ANT and allows for investigative procedures to be used in a reflexive manner and for a continuous evaluation of the process.

1.4 Mixed Research Methods

Mixed research refers to the cases where quantitative and qualitative research methods are used together and integrated into a single study (Frels and Onwuegbuzie 2013; Watkins and Gioia 2015). By incorporating the strengths of each method, the researcher ensures that the weaknesses of the methods neutralise each other and a more complete understanding of the research problem is acquired (Creswell 1994). The combining and mixing of quantitative and qualitative methods is not a new or unique phenomenon. Mixed research has been widely accepted and increasingly used by researchers across disciplines (Frels and Onwuegbuzie 2013). It has proven useful in helping researchers enhance their interpretations by allowing them to better contextualise the qualitative findings. The most common scenario is one of collecting quantitative data and qualitative data simultaneously. Then, a quantitative scale is established that helps to interpret qualitative interviews, and the results are called mixed methods research (Frels and Onwuegbuzie 2013).

Johnson et al. (2007), on the basis of a comprehensive survey and in an attempt to include other aspects beyond the research method, which may also be mixed (e.g. philosophical assumptions and research questions) defined mixed research as follows:

> *an intellectual and practical synthesis based on qualitative and quantitative research; it is the third methodological or research paradigm (along with qualitative and quantitative research). It recognizes the importance of traditional quantitative and qualitative research but also offers a powerful third paradigm choice that often will provide the most informative, complete, balanced, and useful research results* (Johnson et al. 2007, p.129).

The integrative nature of HIRC makes it a perfect fit for a mixed methods research process. While quantitative research is useful for *"answering questions of who, where, how many, how much, and what is the relationship between specific variables"* (Adler and Adler 1994, p.5), it is not very useful for determining the why and the how. The opposite is true for qualitative research. Through the use of mixed methods research, both sets of questions can be simultaneously addressed within a single research study. Quantitative questions can be used to understand the cause and effect relationships of using a robotic partner. Qualitative questions deal with examining the experiences and perceptions of the designers through the collaborative design exercise and would provide an understanding of how people interact, move and use technology. Additionally, by collecting information through two different methods, the research argument can be compared, confirmed, or contradicted (Kumar 2014).

Using a mixed methods research approach has several benefits, amongst which are the following: 1) triangulation of quantitative and qualitative data, enhancing the accuracy and the validity of the findings; 2) finding a quantitative generalisable explanation that is explored in-depth through the non-generalisable qualitative approach; 3) increasing the level of confidence by increasing the accuracy of the research findings; and 4) enhancing the possibilities of answering all the research questions (Creswell 2014; Kumar 2014). However, a mixed methods approach is more time-consuming and resource exhaustive when compared to using a single approach (Kumar 2014). The researcher needs to allow for extra time and additional resources and physical and digital skills for the data collection and data analysis stages.

During a mixed methods research study, one technique is given a higher priority than the other. In this research, a qualitative-dominant crossover mixed analysis is used (Onwuegbuzie et al. 2012). The questionnaires were limited to providing a broad view of the perception of team fluency during the collaborative research exercise. Qualitative data were used to contextualise, analyse, and interpret the results.

1.5 Template Analysis

Qualitative data were analysed using template analysis. Within this analytical technique, a coding template is developed to summarise the emergent themes appearing in the data and the relationships between them. This analytic method is particularly flexible and is well suited to a socio-technical methodology. King, developer of template analysis, establishes that *"template analysis involves the development of a coding 'template', which summarises themes identified by the researcher(s) as important in a data set, and organises them in a meaningful and useful manner"* (King 1998, p.119). Hierarchical coding is emphasised using broad themes, encompassing successively narrower, more specific ones. The template should always be viewed as a means to make sense of the data and not as the product of the analysis (Brooks et al. 2015). The template which starts with some 'a priori codes' to identify the themes that are expected to be relevant to the analysis, serves as the basis for the researcher's interpretation of the data and writing up of the findings (King and Horrocks 2010).

Codes are modified or eliminated iteratively throughout the analysis according to their usefulness and relevance to the data.

Template analysis is a highly flexible but well-structured approach to handling qualitative data. It enables a clear, organised account of the study (King 1998). However, one of its main disadvantages is the lack of a substantial body of literature when compared to other qualitative analysis methods such as grounded theory or discourse analysis. Template analysis allows for openness in the data while imposing some shape and structure on them, without prescriptively transforming the analysis into a quasi-quantitative one.

1.6 Conclusion

ANT was introduced into this dissertation as a suitable approach to describe the implications of an HIRC framework from a more theoretically substantiated angle. The basic assumptions and modus operandi of ANT have been described in the context of an HIRC design ecosystem. Key ANT concepts were included and contextualised for this research, such as those related to **actants** (robots having agency, built-in programmes, and hardware and software limitations), **translations** (how robots and other actants in the network – human and non-human – enter associations to coordinate themselves), **punctualisation** (how the robot is perceived as an entity on its own instead of a sum of individual software and hardware parts), and **obligatory passage points** (critical events for the survival of the actor-network). Illustrating each of these concepts within the framework of a design process allows us to describe the HIRC more holistically. Using ANT as an analysis methodology supports the following: 1)seeing a robot-enabled design process as a complex issue where technology-determinism and social-determinism clash and must be reconciled; 2) acknowledging the role of actants that are not traditionally considered individually (historical design principles and ideas; semiotic elements, such as instruction manuals made for participants; code; algorithms; end effectors; and physical design features); and 4) encouraging the effort to investigate the topic empirically (using case studies and participatory action research).

ANT as a methodology has greatly contributed to areas of research where human and non-human agents work together. As robots become an increasingly important part of humans' daily life, ANT offers a conceptual and theoretical framework to analyse their contributions and the new relationships that are formed. An important aspect of turning to ANT is Latour's focus on the co-production of knowledge and his belief in replacing explanations with descriptions. The final argument for the application of an ANT approach to this research is the understanding of how human−robot teams work. Although the robot in this exercise is not autonomous, it has the ability to offer feedback and can perform the task without the human. The emphasis on allowing the human to make decisions at each step of the task is to accommodate the vision of humans and robots working together as an organic asset. It could be argued that it is not only the behaviour of each team individual to be judged but also the behaviour of the entire team. This is fundamental to answering the research question: which behaviours would need to be designed in an HIRC design task so that both, robots and humans, contribute not only to the task but also to the cohesion of the team? A scenario in which robots are contributing and being held responsible for the results of the team requires a socio-technological approach.

ANT provides a socio-technological view of the design activity. It provides a systemic view on the interconnections between the heterogeneous technical and non-technical elements. These interconnections become networks between these elements. Once a network is created, it will shape how the elements act, interact, and influence each other. The symmetry in agency that ANT gives to all the different elements within the network, whether human, software, material, design conceptions, or robot manipulator, results in a scenario of dynamic mutual influence within a relational notion of agency. This yields very important consequences of how we understand the collaborative design activity and how we assign the notions of responsibility for the resultant design, as it will be beyond the individual actor. Initial design decisions might be the result of individual actions, but the ultimate result has to be considered to be a product of the interactions between the actants that resulted in specific actions and hence design decisions. It could be argued that the decision-making always stays with the humans; however, the mutual influence between the designer and the robot that is shaping agency and resulting in such decisions cannot be taken out of the equation.

This research question involves many variables such as collaborations, empathy, design improvement, and material behaviour, and thus, a reductionist laboratory method will not be sufficient. Shneiderman (2008) has called these new collaborative, socio-technical areas of research *"Science 2.0*". They require new ways to study complex interactions that promote integrative thinking and combine the technical know-how with social sensitivity. Further, we need innovative multi-method approaches for understanding what makes these socio-technical systems successful.

This research combines quantitative questionnaires with qualitative data obtained from semi-structured interviews, videos, and field notes. The decision to select a mixed methods approach was taken to maximise the in-depth description of the collaborative phenomenon: how did the participants feel and what aspects of the robot arm manipulator excited them, worried them, or made the process different? Written accounts or closed questionnaires alone would not produce the depth of information and the description of the networks and relations between the different actants required for an ANT interpretative analysis of the collaborative phenomenon. A mixed methods research approach allows the researcher to probe further, ask for elaboration where necessary, and tease out the information in order to produce a complete picture of the lived experience of the collaborative process. Template analysis was selected to analyse the qualitative data as it keeps the descriptive nature of ANT while giving some structure and shape to the data and without over constraining them.

Chapter 2 SOURCES AND DEVELOPMENT OF A HUMAN–ROBOT COLLABORATIVE DESIGN PHENOMENON

2.1 Introduction

This chapter reviews the relevant literature regarding the implementation of HIRC. It starts by providing an overview of robotics, their evolution and introduction into architecture. Section 2.4 introduces the concept of collaboration and HRC, particularly in the area of industrial robotics. Section 2.7 discusses the importance of adopting a human-centred approach towards the introduction and implementation of new advanced technologies.

2.2 History of Robotics

"They whir, they buzz, they spin, and rumble. A world is a fabric of machines" (Bryant 2014, p.37).

Robots have always intrigued humans; they have been featured in plays, books, cartoons, and films and captured our imagination, particularly after the 1960s, an era of great technological progress and fascination with technology. Nevertheless, there are earlier depictions of robots, always portrayed as very intelligent machines, usually with human-like features or attitudes (e.g. Maria in *Metropolis* in 1927 and Robbie in *The Forbidden Planet*, 1956) (Figure 2-1). Robots are usually depicted as creatures in the mould of a human which are under the control of their creator. The original *Star Wars* from 1977 brought the two most famous fictional robots R2-D2 and C-3PO (Figure 2-1); they are amazingly intelligent, able to hold full conversations with people, and execute difficult engineering tasks that need not only mechanical strength but also brainpower. It is only more recently with the film *Robot & Frank* (Figure 2-1) that a more plausible scenario is shown, one where the main character is assisted by a robot that guides him to be a better person. Here, the robot is depicted as a collaborator that is able to converse with humans, but most importantly, to help them perform tasks together (Corke 2015)

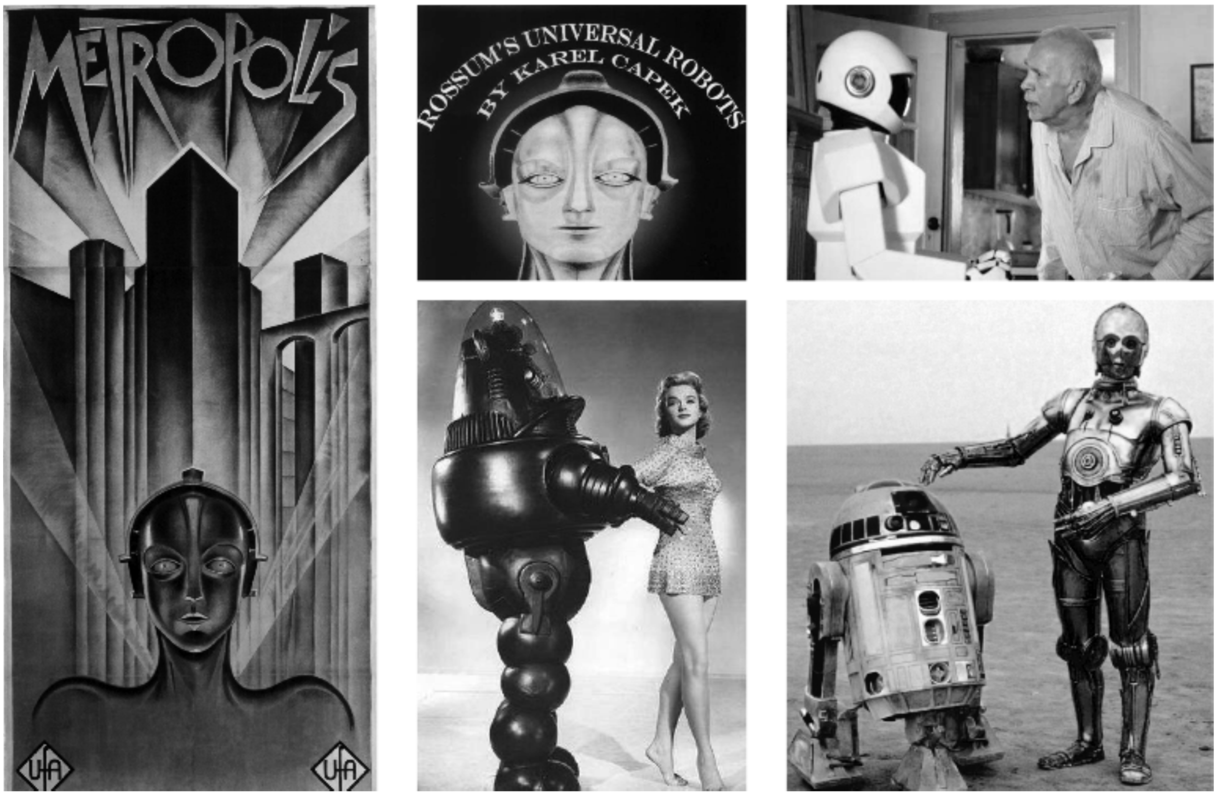

Figure 2-1 Left: Metropolis poster (Helm et al. 1927). Middle top: RUR (Capek 2012). Middle Bottom: Forbidden Planet film poster (Wilcox 1956). Right Bottom: Star Wars (Lucas 1977). Right Top: Robot & Frank (Schreier 2012).

The concept of a robot has advanced and moved from sci-fi into reality, particularly in the last 50–100 years (Figure2-2). Nevertheless, it is not new, Aristotle was already talking about them in ancient Greece: “If every tool, when ordered, or even of its own accord, could do the work that befits it… then there would be no need either of apprentices for the master workers or of slaves for the lords” (Ewalt 2012, p.4). However, the Czech Capek only coined the word ‘robot’ in 1928; it means ‘slave or worker’. He used it for his play RUR Rossum’s Universal Robots (Figure 2-1) in which people create robots to relieve them of the drudgery of everyday tasks, until the robots resent their role in society and ultimately kill their human masters.

However, in robots, either in fiction or in reality, there has always been a very strict Cartesian division between body and mind (Bonsignorio 2015). This became more evident in 1951 at the Argonne National Laboratory where the necessity to manipulate dangerous radioactive materials led scientists to develop a system for ‘teleoperation manipulation’. A set of ‘slave’ arms (Figure 2-3) would be placed in a remote room holding the radioactive material, while scientists perform the task remotely using ‘master’ arms. The slave arms replicate the task in a close to real-time mode. This machine can be considered to be the precursor of modern robotics. In modern industrial robotics, the computer acts as a master arm, but usually, the operation is not replicated in real time (Corke 2015).

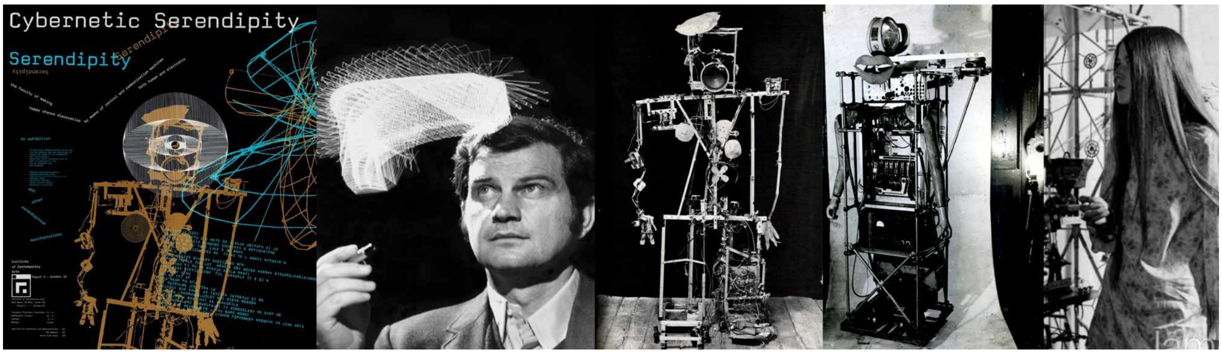

Figure 2-2 Cybernetic serendipity exhibition (1948).

Automata machines that developed in the 1700s started to explore the ideas of interaction and human-like functions. They were clockwork pieces of engineering made to look very lifelike that simulated human or animal functions. An example of this is Vaucanson’s digesting duck (Figure 2-3) capable of eating grains, digesting and defecating them. Although it was only mimicry, it embodied a desire for a lifelike automated robotic machine.

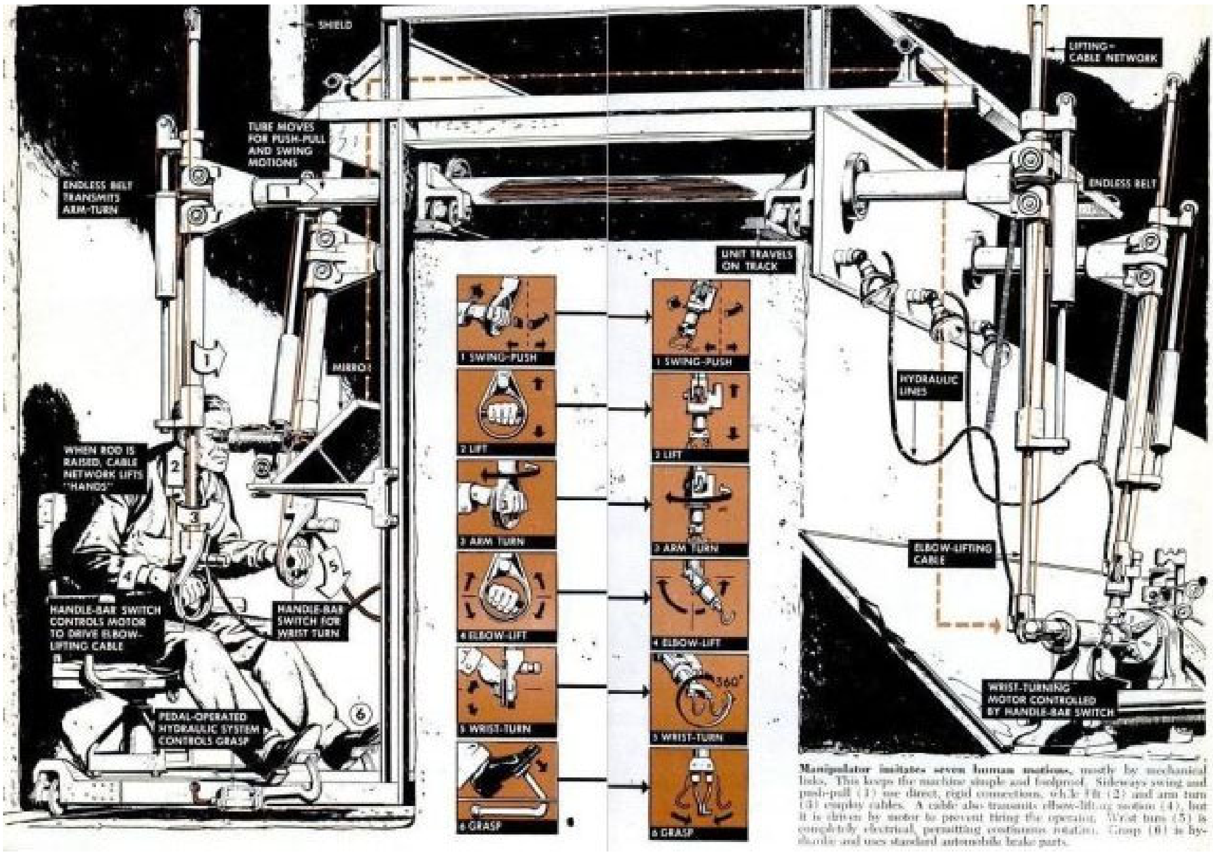

Figure 2-3 Payne manipulator. The robot is only following instruction from a set of arms in another room. Source: http://cyberneticzoo.com/

A very early example of the desire for a human–robot collaboration was the Turk (Figure 2-4), a chess player that was a mechanical humanoid, designed and built by Wolfgang von Kempelen in the late eighteenth century (Windisch 2010). It was a complex mix of functional and fake clockwork, all covered with maple veneer to provide the illusion of an autonomous, intelligent machine while covering its true mode of operation. The Turk in reality was a complex mechanical marionette, and a real chess player hid inside it to control it. The great thing about this machine was not its complex clockwork engineering, but the idea of covering all of its mechanical attributes so precisely as to convey the image of a machine that thinks and acts as a person and that can beat human chess players. This is considered to be the first intent of blurring the divide between the body and the mind of the machine, an idea that still pervades modern-day robots, and of building an autonomous robotic device capable of interacting and responding to the human mind (Özel 2014).

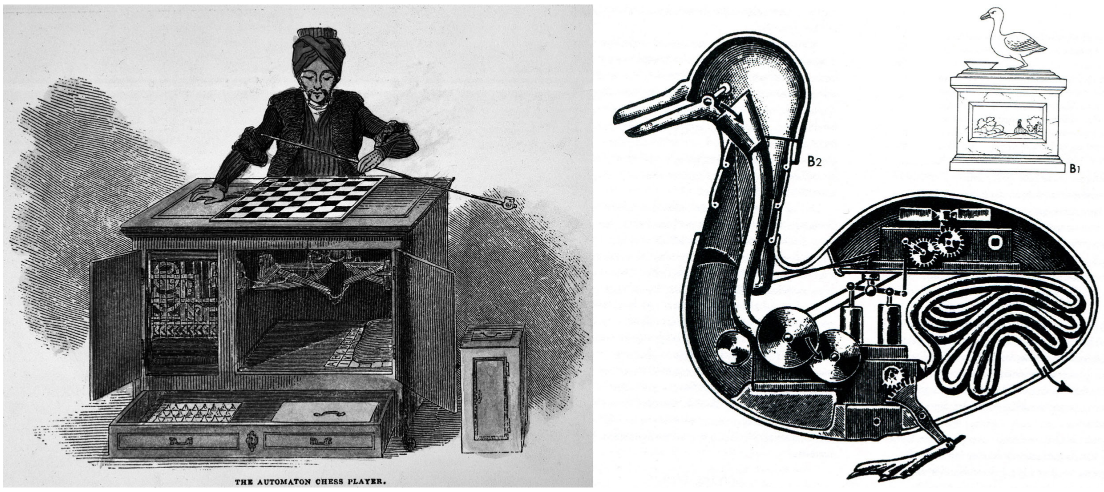

Figure 2-4 Left: An engraving of the Turk (Windisch 2010). Right: Vaucanson's mechanical duck (Wilson 2013).

During this period of time, some more useful machines that can be considered mechanical precursors of the current robot and computer were made. After his duck, Vaucanson went on to develop a machine that automates the process of weaving. Jacquard later perfected these principles and used them in Jacquard's loom (Figure 2-5). Similarly, during this time, Babbage developed a general-purpose machine in which the input was controlled by punching cards (Figure2-5). This was the beginning of the development of computers and subsequently, of robotics.

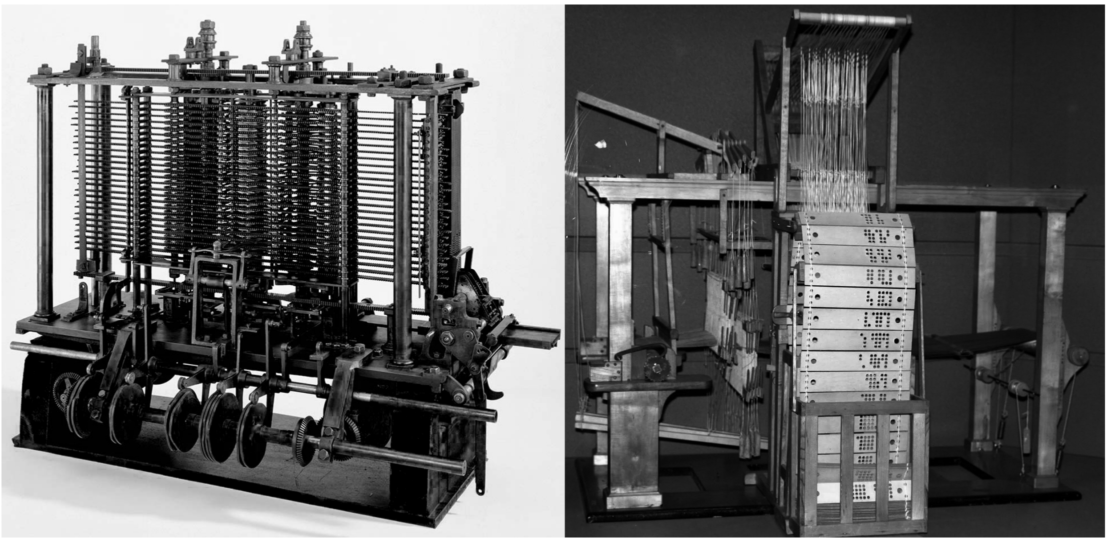

Figure 2-5 Left: Babbage's analytical engine. Right: Jacquard's loom (Groover 2017).

Aside from many romantic perceptions, *"robots are first and foremost computers*" (Morel 2014, p.85). The limits of what is and what is not a robot have not been agreed upon, thus creating an ongoing philosophical and scientific debate. Definitions range from the very general inclusive ones to the very complicated and ontological. The Oxford dictionary (OED Online 2017) defines a robot as a *"machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer"* a definition that can easily include blenders, printers, and other appliances. William Gevarter (1983, p.2), in contrast, defines a robot as "*a flexible machine capable of controlling its own actions for a variety of tasks utilizing stored programs. Basic task flexibility is achieved by its capability of being reprogrammed. More advanced robots would be capable of setting their own goals, planning their own actions, and correcting for variations in the environment".* Calo et al. (2016, p.5) go further, questioning their ontology, *"a robot is a constructed system that displays both physical and mental agency, but is not alive in the biological sense".* The preferred definition in the context of this dissertation is the one from roboticist Peter Corke (2015, p.4) who writes "*a robot is a computer that can do things in the physical world"*. It encapsulates robots as constituted by a system of two parts: a physical manifestation that acts and senses, and a system that drives its behaviour. The requirement of interactivity and feedback with the physical world and its actors is a key aspect in this research.

2.3 Robots in Architecture

Since they first appeared in the 1950s, robots have increasingly permeated into every aspect of human life. Robots and automated machines in manufacturing processes worldwide have manipulated almost any item that humans may consume today (e.g. cars, food, clothes and electronics). Moreover, the machines have been increasingly leaving industry to be incorporated into our living and working environments, from automated vacuum cleaners to assistance devices and soon autonomous vehicles. Industries such as healthcare and military now count robots amongst their everyday staff. Robots, like computers, have gone from large, expensive machines only accessible to industry and researchers to smaller, accessible machines. This together with the recent democratisation of digital fabrication tools like 3D printers, laser cutters or computer numeric control routers, has renewed the interest in the field of robotics from more creative communities (García del Castillo y López 2019). In the last 30 years, robot arms have become ubiquitous to schools of architecture and research laboratories, the Association for Robots in Architecture lists over 75 institutions and more than 130 robots (Rob|Arch 2019). Architecture schools are increasingly incorporating robotics as part of their curricula. Conferences dedicated to promoting research in this field have become established (i.e. Rob|Arch 2012–2018), and larger spaces are being opened for them.

Research on robots for architecture and the construction industry is not recent. A range of interesting and compelling studies to automate and introduce robots into the construction workflow has been documented since the 1970s, particularly in Japan (Bechthold 2010). Most of the efforts were directed initially towards methods for construction automation through prefabrication, with a certain degree of ability for customisation. Later efforts focused on single-task robots that could be deployed on site with the final goal of designing construction sites that work like factories (Figure2-6) (Bock and Langenberg 2014). What is new, in this era of robotics in architecture, is that unlike the previous attempts, the focus has not been on automating human processes to make construction cheaper and more efficient, but on how to use the robot to 1) build complex, novel geometries for humans, and 2) to explore novel materials and techniques (Gramazio and Kohler 2008; Gramazio et al. 2014). The work has focused on developing the design as well as the tools.

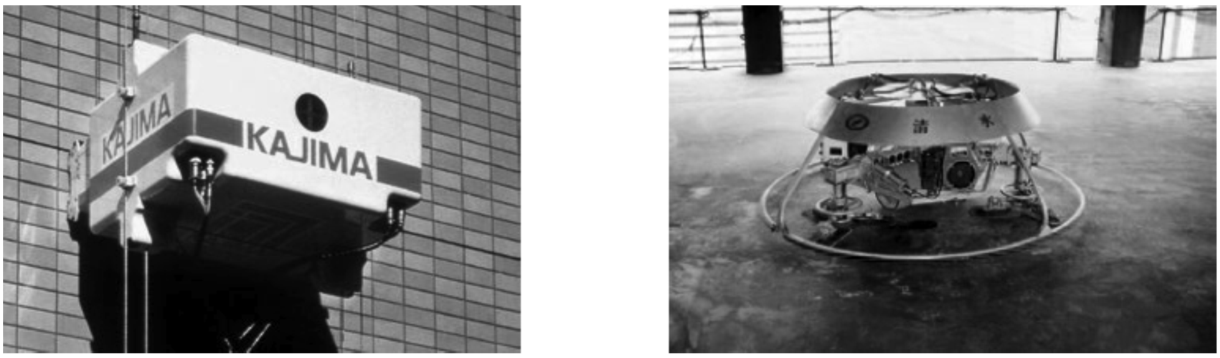

Figure 2-6 Left: Kajima Corporation, Façade inspection robot, Tokyo 1988. Right: Shimizu Corporation, Concrete finishing robot, Japan 1987.

Greater computational literacy within the architecture discipline, more powerful and distributed computing capabilities, and the emergence of open-source platforms to integrate physical sensing and actuating like Arduino (Mellis et al. 2007), provided a simple and intuitive development environment. These coupled together resulted in a growing community of architects using and experimenting with the possibilities that robotic fabrication brings to architectural practice empowered by the tools to experiment and make almost anything. Projects such as RoMA (robotic modelling assistant) (Peng et al. 2018) demonstrate the potential of integrating sensing robots in design-while-making systems. Artistic projects like Mimus (Gannon 2018) and Mimic (I/O 2017) have explored the expressiveness of six-axis robots beyond simple tools.

2.4 Human–Robot Collaboration

As long as technology was represented exclusively by the machine, it was impossible to speak of 'man and the machine'. The machine remained an external object, and the man was in a position to assert himself apart from the machine. But when techniques enter into every area of life, it ceases to be external to man and becomes his very substance (Ellul 1973, p.6).

By 2020, there will be more than 3 million industrial robotic arms installed worldwide, which means they will work closer to people (Blair 2015). The need for human and robot co-existence and collaboration will increase. Historically, they are heavy, brittle machines with very powerful motors but little flexibility and few, if any, sensors. They have evolved to move with great speed and precision and have been perfected in terms or reliability and efficiency. They are not very intelligent and are not expected to come up with any unexpected behaviours or any ideas of their own (Pfeifer and Bongard 2006). These robotic arms normally operate in controlled purpose-built environments and execute a single, repetitive task for which they have been programmed once. Although robots have been around for a long time and their development has accelerated in the last 30 years, they still suffer from Moravecs' paradox which states *"things that are easy for humans are difficult for robots while high precision tasks that are difficult for humans are easy for robots"* (Goldberg 2015, min.4:15). In a collaborative scenario, this concept means that the weaknesses of the human can be complemented by the strengths of the robot and vice versa (Bortot et al. 2013) (Figure2-7).

The urge to get the robots out of their cages has been noticed by industry. As robots move away from their constrained, planned environments and move into the human, messy, unpredictable world to be our collaborators they need to become more elastic, flexible, gentle and aware of their environment (Nourbakhsh 2013). Robot manufacturers have realised this desire and it has motivated them to research and fabricate new robotic arms with built-in spring systems, sensors and less intimidating colours, examples of this are the robots developed by the Danish company, Universal Robots, and the KUKA LWR lightweight robot. Rethink Robotics developed a different approach to collaborative robotics with Baxter, a robot with two industrial arms and a face, which allows the user to know what the robot is looking at. These robots present exciting possibilities as they can truly work next to humans (Figure 2-8).

Figure 2-7 Alexander McQueen 1999, Savage Beauty, the final dress paint was an interaction between the robot's and model's movements and actions (McQueen 2011).

Figure 2-8 Left: Typical industrial robot. Middle: KUKA LWR. Right: Baxter (Bonsignorio 2015).

Humans and robots can establish meaningful collaborations where they can benefit from the strengths of each other and work as partners towards a common human objective. The most successful HRCs today are in underwater or space operations where robots have sensors and autonomy for some tasks but are also remotely controlled by humans in real time in what is called ‘teleoperation’. The most flexible component of a manufacturing system is the human operator. After a race for full automation, the manufacturing industry has come to realise that *“ensuring a meaningful involvement of people in decision-making and operation of manufacturing robots is critical to their success”* (ElMaraghy 2005, p.262). Against predictions from the early AI enthusiasts in the 1950s, today, humans remain *“incredibly adaptable, dexterous as well as fast, skilled and cheap when compared to robots”* (Gevarter 1985, p.125).

2.5 Defining the Collaboration

The term collaborative has been defined in different ways according to the nature of the task to be performed. Different collaborative tasks (e.g. conversations, intellectual teamwork, and division of manual labour) change expectations of what should be each member’s contribution, the appropriate forms of control, delegation, reward, and the distribution of credit and blame (Goodnow 1996). In the context of human–computer collaboration (HCC), collaboration is defined as a *“process in which two or more agents work together to achieve shared goals”* (Terveen 1995, p.1). Collaboration in this way has enabled two different approaches: the first one tries to endow computers with human-like characteristics to enable them to act like humans and engage in collaborations similar to human–human ones. The second approach tries to get computers to collaborate with humans by exploiting their unique abilities in a way to complement humans. Licklider (1960) defined this second approach as a man–machine symbiosis. Traditional symbiotic partnerships between man and machine, involve *"men setting the goals, formulating the hypothesis, determining the criteria and performing the evaluations, while the machine does the routinizable work to prepare the way for insights and decisions"* (Licklider J.C.R. 1960, p.1). He had already anticipated that man through these symbiotic partnerships would be able to perform intellectual operations more efficiently than alone. Collaboration can be defined then as *"working jointly with others or together, especially in an intellectual endeavour"* (Green et al. 2008, p.1). An interesting thing to note is that social factors shaping human–human interactions apply equally to human–computer interactions (Nass et al. 1994).

2.6 Background: Human–Robot Interaction

Interaction between humans and robots has existed since the 1940s. This interaction has been primarily unidirectional in which the robot follows instructions from the human as with teleoperation robotic platforms. As robots become smarter and leave their constrained settings to become involved in unstructured, complex tasks, they have closer interactions with humans. The closeness goes beyond the physical workspace to include sharing goals and tasks which require different theoretical models that evaluate their risks and benefits as human collaborators in capacities beyond utility tools (Sheridan 1997). Robots have thus become part of an interdisciplinary field of research broadly considered human−robot interaction (HRI) (Goodrich and Schultz 2007).

HRI is a field dedicated to the study, understanding, design, and evaluation of robotic systems to be used by or with humans. It is based on the existence of interaction, defined as communication between humans and robots in the system (Hancock et al. 2011b). HRI can be defined as *"the study of the humans, robots and the ways they influence each other"* (Fong et al. 2001, p.2). HRI is only one subset of the larger issues of human−automation interaction.

Despite some areas where automation and robotics blend and the blurring of the general principles of automation with those of robotic entities, it is safe to consider HRI to be a field of its own when compared to human−machine interaction (HMI) and to human−computer interaction (HCI) (Hancock et al. 2011b; Billings et al. 2012). The differences are in several dimensions. Fong et al. (2001) noted that HRI is different from HCI and HMI, because it deals with systems which have complex dynamic control, exhibit autonomy and cognition, and operate in changing real-world environments. Robots, differently from general automated systems, are mobile, have a range of physical embodiments, can have a variety of tools or end effectors to fit different purposes, and have different degrees of anthropomorphism. Additionally, humans have been observed to react differently to interactions with robots than with other automated systems. Hence, robots need to be studied independently from automation, as they introduce a degree of uncertainty that automation does not (Desai et al. 2009).

Human−robot collaboration (HRC) is a subset of HRI focused on studying human−robot interactions when they are executing tasks in a shared workspace (Alami et al. 2006; Pellegrinelli et al. 2016a). Within a set of given actions or tasks to be performed (e.g. open or move) and a set of objects on which to perform the task or goals (e.g. door or cup), humans can select which tasks to perform and on which goals to perform them. The robot can:

1) perform an uncorrelated task on a secondary goal (Mainprice and Berenson 2013);
2) perform another task on the same goal to support the human during the execution of the task (e.g. hold a bottle the human wants to draw on); or
3) perform a related task on another goal (e.g. open a drawer for the human to retrieve something) (Koppula and Saxena 2016).

HRC aims to produce robot behaviours which are complementary to human behaviours while optimising human satisfaction and comfort (Kulic and Croft 2003; Pellegrinelli et al. 2016a). Humans have priority over robots during the task selection in the majority of the HRC approaches.

HRC has been investigated in the literature in various forms; however, the aspects of fluency and the meshing of human and robot actions have received less attention (Hoffman 2013a). Studies on robotic arms assisting humans in assembly tasks are common. For some researchers, such as Kimura et al. (1999), the focus has mainly been on issues of vision and task representation rather than fluency and team dynamics. Other researchers, such as Fong et al. (2006) and Jones and Rock (2002), have focused on issues of dialogue and control. Collaboration in their systems mainly takes place by one agent asking for help from another while dealing with a situation. Mechanical coordination and safety aspects in shared human–robot tasks have also received attention (Wörn and Längle 2000; Khatib et al. 2004). Hoffman and Breazeal (2012) focus on turn-taking and joint plans in HRC tasks. Hoffman and Breazeal (2007) have also focused on robots that can learn jointly with humans and can communicate both verbally and non-verbally. Recently, systems that can anticipate human behaviour on the basis of knowledge databases and decision processes (Lenz et al. 2008) which can ensure an effective collaboration have become central to the research on HRC. The robots in these last systems can perceive their environment and recognise human intentions due to a variety of sensors that inform their collaborative actions through multiagent control architectures using machine learning and Bayesian networks (Schrempf et al. 2005).

2.6.1 Human–Industrial Robot Collaboration (HIRC)

The concept of industrial HRC, where robots have a long history, is nascent compared with robots in other fields and has limited applications. HRC with industrial robots has been developed with the aim of a structure in which human operators perform the *"value-added work"* while robots take over the repetitive and *"non-value-added work"* (Unhelkar et al. 2014). Relations are mainly based on a master–slave level where the human worker teleoperates or programmes the robot offline, allowing for a limited set of actions. In traditional manufacturing industries, such as automobiles, humans are completely excluded from production lines and robots are generally not integrated with human workers. The potential of humans and robots working together as a team on manufacturing tasks is starting to be explored. Different approaches to take advantage of the HRC in HRTs are emerging. Mixed-control systems, as an example, in which each member, based on its capabilities, can assume control over the task at different moments with roles changing throughout the duration of the task (Pellegrinelli et al. 2016a). HRC teams offer flexibility and adaptability to production scenarios allowing them to change their environment towards the manufacturing of highly customised products and requiring humans and robots to support one another in different ways (Lenz et al. 2008).

HIRC could thus be considered to be different from HRC because of the characteristics and thought processes traditionally used for the design of the system, its evaluation, and the related task planning. In the field of architectural design, where robots have a shorter history, the concept of HIRC during design tasks is still a relatively unexplored field of study.

2.7 Human-Centred Approach for Technological Change

Kidd (1992) notes that human skills are always needed in robotic systems; he further argues that designers should use robotic technology *"to support and enhance skills of the human as opposed to substituting skills of the robots for skills of the human"* (Kidd 1992, p.136). However, human-centred design has not been a constant feature in the design of robots and, more specifically, industrial robot arms. Until recently, the focus of robotic researchers and designers was on complying with legislative requirements, such as safety, which includes cell layout, software safety issues, and in general, making the technical system safe. In order to make HRIs successful from a human-centred approach, it is crucial to look beyond the technological issues and to consider issues such as task allocations between people and robots, group structure, and team fluency. The following four key features have been identified as fundamental in a human-centred robotic system: 1) to support and enhance human skills, 2) social science knowledge is applied in its design, 3) social knowledge is applied during the shaping of the technology, and 4) the focus of the design process is interdisciplinary (between technology and the social sciences) (Kidd 1992). Incorporating and researching human factors in HRC processes has to include more than just the interface for the user (Waldeck 2000).

Falcone and Castelfranchi (2000) define ‘strong dependence’ as situations in which robot agents provide relief to human agents not because the task is boring and repetitive but because the task requires delegation as the human agent does not have the local, decentralised, and updated knowledge or expertise; precision; or some physical skill that is required. Furthermore, they established that effective collaboration requires an adequate distribution of goals, knowledge, and competence (Falcone and Castelfranchi 2001). The aim is to create HRTs that take advantage of the skills of each team member, allowing them to fully utilise them. A human-centred approach to the HIRC design process means that the results should be evaluated not only for their impact on people but also that the technological ideas should be shaped by social insights in order to produce a better outcome.

During the design and implementation of new technologies, the existing literature agrees that carelessness in considering the human element is detrimental to the results. Problems arise during the implementation of human–machine collaborative practices generally because of the way in which the human element is affected (McDermott and Stock 1999). Relevant human and robot factors that enable the interaction and constitute a framework for it should be considered from the early stages of the technological implementation and design; otherwise, the issues become secondary and have little impact on the design and task considerations (Kidd 1992; Scholtz 2002a). Considering the human factor is not new. Human capabilities, human performance, and human cognition are essential for any HRC system. However, they are much less frequently discussed. Parasuraman and Riley (1997) argue that this is not because of a lack of knowledge but because of a greater collective emphasis on the technological rather than human aspects of technology. However, the real gains from any new technology can only arrive once these technologies adapt to humans. It has been proven not to be sufficient for only humans and businesses to adapt to the technology (Arthur 2010).

2.8 Different Stages of the Collaboration

New technologies have to evolve through the various stages of human–automation collaboration in which they inform each other. The human has to become used to the

characteristics of the machine and the machine has to refine its characteristics to satisfy human needs. Pieters and Winiger (2016) described the evolution of automated systems in three parts:
1) First-generation systems, which mimic analogue tools with digital means. Even with these characteristics, they help non-experts to become more creative (Figure 2-9), for example, the 1980s first generation of Photoshop, Autocad, and MS Word.
2) Second-generation systems which start to negotiate the creative process with humans through feedback loops. In these cases, the machine starts to be provided with more agency, and decisions can begin to be collaborative in the system. For example, autocorrect and autofocus.

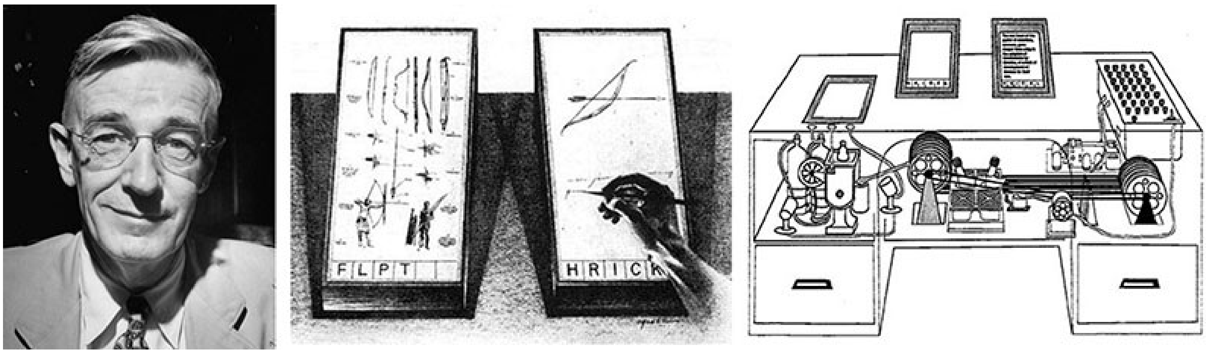

Figure 2-9 Vannevar Bush / Memex (1949).

3) Third-generation systems are what have been called assisted creation systems. The aim is to design these systems such that they can *"negotiate the creative process in fine grained conversations, augment creative capabilities and accelerate the skill acquisition from novice to expert"* (Pieters and Winiger 2016, p.22). For example, assisted drawing systems that correct the strokes to help illustrators draw and assisted writing systems that improve the writing style. HIRC in design tasks can currently be considered a second-generation system (Section 3.6).

2.9 Robotic Arms: Anatomy

Robot arms are proven robust off the-shelf platforms that are sufficiently flexible to accommodate the needs of the designer (Braumann and Brell-Çokcan 2012). They are not smart tools; they rely on offline programming sequences and will only do whatever they are programmed to do. Robot arms are mechanical structures composed of interconnected joints and links (Figure 2-10). Links are the rigid parts of the robot. Joints provide the relative motion (rotation or translation) between two parts of the robot or links, similar to the human body. Each joint has an input and an output link that it connects. The joints, also called axes, indicate the degrees of freedom in the robot's motion. Industrial robots are generally described by the number of axes or degrees of freedom that they possess (i.e. a six-axis robot). Robot arms can be designed in different sizes, colours, and loading capacities (payload) according to the application for which they are required.

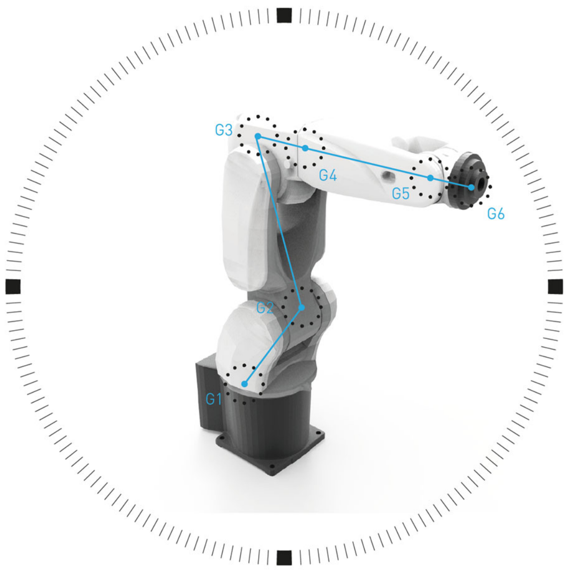

Figure 2-10 Joints and links of a six-axis industrial robot arm.

Industrial robots are normally designed as a single or a twin arm. Recently, some developers have added human features such as face and eyes to the robot with the aim to increase its human-likeness (e.g. Baxter, a robot with two industrial arms and a face, which allows the user to know what the robot is looking at).

2.9.1 Teach Pendant

The main human–machine interface for robotic arms is the teach pendant. The teach pendant is a simple keyboard attached to the robot computer and can be used to guide the robot to different points. Through the teach pendant, it is possible to control the rotation and position of each of the joints, control the position and movement of the end effector, control the robot's movement and speed, and create programs. The pendant cannot be operated intuitively, and the proprietary language of different robotic arms limits their user-friendliness (Lin and Lin 2014)

2.9.2 Programming a Robot

A robot arm has to be told how to operate through a set of actions and commands controlled by the computer. There are three main modes to program a robot arm:

- Lead-through: the simplest type of robot teaching. A human operator guides, or leads, a robot through the movements of a job. The computer memorises the movements, and the robot can then repeat the task it has been shown. It requires a skilled human to guide the robot arm and can only be used for known motion sequences.
- Walk-through: In this case, the operator uses the teach pendant. Through the teach pendant, the robot can be jogged up, down, left, and right, and the positions can be recorded and replaced. Once the points are recorded, the computer works out how to route the robot arm between these points.
- Offline programming: This is the third method of teaching. In this method, the operator types the exact instructions for the robot's motions in a computer. These instructions are then translated into a series of electronic signals that guide the robot's movements. Actions in addition to these movements are also programmed to create a complete program for a defined task.

In a design scenario, the design object exists in the digital world but not in the physical world. While lead-through and walk-through programming methods work for repetitive tasks, they may not feasible for individualised production processes, such as the design activity. In an architectural context, robotics is concerned with unique parts that are usually designed and developed within digital CAD software and with more complexity than what can be manually taught to a robot (Feringa 2014). Thus, a different way of engaging HRC needs to be designed for architectural applications.

The lack of integration from established robot programming modes with CAD and design platforms has caused the surge of plugins for CAD software built by architects and designers. They work inside traditional design packages such as Rhinoceros and its plugin, grasshopper. They range from kinematic solvers to simulate and generate robot paths, e.g. KUKA PRC (Braumann and Brell-Çokcan 2012; Johannes Braumann 2017) and HAL (Bonwetsch 2012), to those that encapsulate the expertise required to assemble structures made out of large quantities of discrete components, (e.g. *Scorpion,* a Rhino plugin for robotic laying of bricks and mortar (Elashry and Glynn 2014), and *BrickDesign,* a software tool also for bricklaying by ROB Technologies (Bonwetsch et al. 2012)). These developments generate robot paths while allowing design within the tool, something not common to traditional robotic programming tools. A different set of tools is being developed to allow real-time control, (e.g. Machina, a library for real-time robot control which allows robots to communicate with other apps such as virtual-reality headsets and game controllers (García del Castillo y López 2019)).

Additionally, systems for collaborative control in which the human gives advice but the robot can decide how to use it (Fong et al. 2006) have become central to research. In these systems, the robot follows a higher-level strategy, previously set by the human, with some freedom in the execution. As robots become more adaptive and self-aware, higher levels of programming than those limited to very specific actions will become common.

2.9.3 End Effectors

Robots differ from other numerically controlled machines such as CNC-millers and CNC-cutters that are digitally controlled versions of well-established processes. Robots are generic pieces of hardware (Menges and Beesley 2014) and only become specific through custom-designed and built end effectors. End effectors are located at the end of the robot arm and allow different interactions with the environment and accomplishment of various robot tasks according to their own specific design (Figure 2-11). In industry, end effectors are classified into two main categories: grippers and tools (Groover 2008). The first ones are used to grasp and manipulate objects, have different shapes, sizes and loads and are divided according to the mechanism they use for grasping (e.g. mechanical, vacuum, magnetic). The second ones are used by the robot to perform specific operations on the parts that it is manipulating (e.g. welding guns, spray painting).

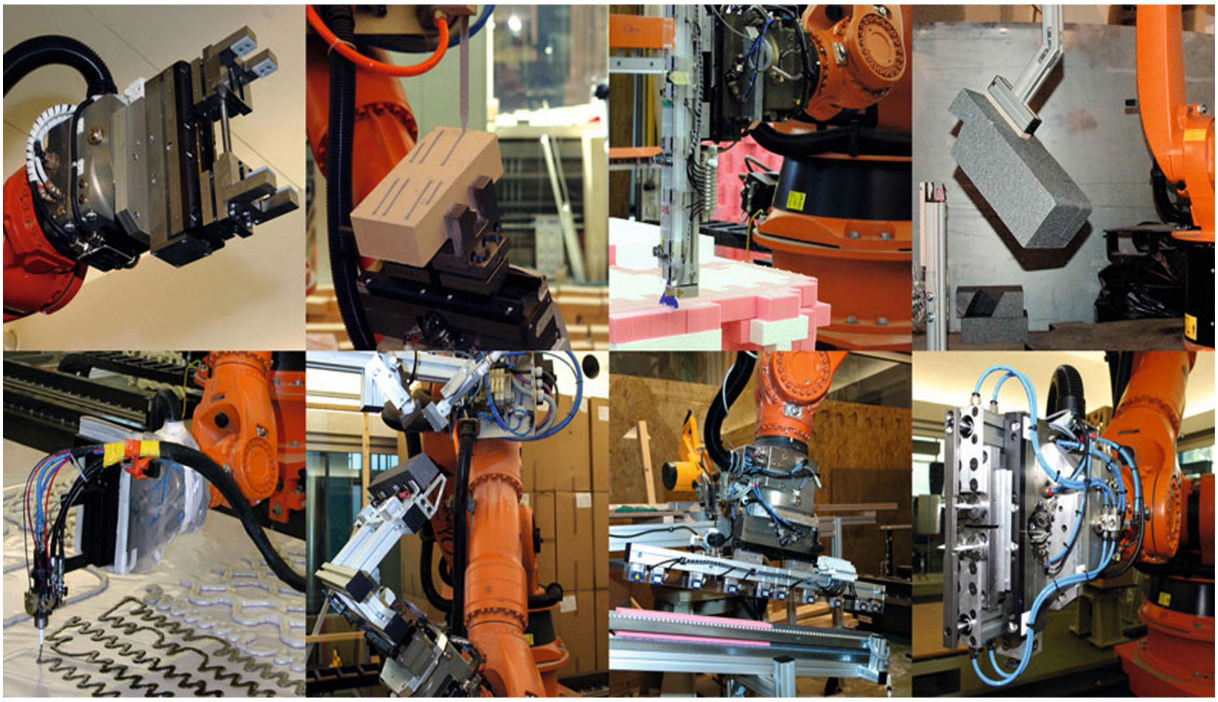

Figure 2-11 Catalogue of end effectors (Gramazio et al. 2014).

2.10 Summary

The aim of this chapter is to provide a general introduction to robotics and HRC, which sets the hypothesis of this dissertation within a wider context. It provides insights and arguments for a robotic collaboration that is not currently visible. Robots are populating the architectural design and fabrication fields. However, only a small part of the existing literature focuses on exploring HIRC and it is normally focused on factories and industrial settings. The domains of integrated manufacturing technologies and their implementation were investigated to understand how humans react to the introduction of machines (chapter 4). The collaboration between humans and robots on task-related processes prompted the review of the major domain of HRI.

The evolution of robots and HIRC in industry has pointed to their huge potential in other areas. Successful implementation of HIRC in the design task can potentially increase the knowledge of the designer by creating roles that exploit the skills of the human and those of the robot, making them work towards the same goal. Collaboration can enable the human and the robot to complement each other. However, research in HRC has indicated the importance of considering the human factor prior to the implementation of technological change. As the numbers of robots increase in architectural settings and tasks, it is crucial to understand how their presence affects designers and how designers feel about them (Nomura et al. 2006). People’s attitudes can affect and bias interactions. HIRC outside traditional manufacturing settings is influenced by people’s attitudes and understanding of industrial robots. However, people’s perceptions of industrial robots are a vast area of research that has not been thoroughly investigated; most of the research has been focused on investigating people’s attitudes towards social and domestic robots.

Chapter 3 SHIFTING THE AGENCY MODEL

I would like to contrast two different philosophies of design, or what amounts to the same thing, two different theories of the genesis of form. In one philosophy one thinks of form or design as primarily conceptual or cerebral, something to be generated as pure thought in isolation from the messy world of matter and energy. Once conceived, a design can be given physical form by simply imposing it on a material substratum.
The opposite stance would be represented by a philosophy of design in which materials are not inert receptacles for a cerebral form imposed from the outside, but active participants in the genesis of form. This implies the existence of heterogeneous materials, with variable properties and idiosyncrasies which the designer must respect and make an integral part of a design process which, it follows, cannot be routinized (De Landa 2002).

3.1 Introduction

Chapter 2 analysed the history of robotics, industrial robotics, and their arrival into architecture and design practices. It also identified the importance of a human-centred approach which attends to the human element during the implementation and adoption processes of new technologies. This chapter discusses the evolution and development of the design activity in relation to the adoption of new technologies. It identifies and collects key theoretical human and material factors influencing the concept of agency in the design process and speculates how they can be instrumental in the successful implementation of design HIRC. The chapter starts by exploring the relationship between craft, design processes and physical materials. It then discusses the agencies in the design process, their relationships and evolution, and the theoretical factors that underpin them, as identified from the literature. Finally, Section 3.12 summarises the chapter and discusses a shift of agency in the design process enabled by novel technologies.

3.2 Craft in the Digital Age

"The artisan does not analyze and quantify but makes and senses through the body's digitally mediated prosthetic extensions and finds form by trial and intuition" (Carpo 2012, p.102).

Pye (1968) made a well-known distinction between the *workmanship of risk* defined by the process of making and the world of the materials and the *workmanship of certainty* defined by the world of manufacturing and mass production. He further clarified that the risks are not only in the materials but also in any type of technique where there is uncertainty with respect to the results because they depend on a variety of external factors that put the result continuously at risk during the process of making (Pye 1968). This differentiating relationship becomes particularly interesting when adopting relatively new design processes within traditional manufacturing tools where the results are neither completely predictable nor controlled. In such a scenario, the digital model no longer prescribes a form into the material but gives the form the capacity to emerge by embedding the necessary information in the material itself (i.e. enabling other non-human agencies during its formation).

Since the 1960s and the 1970s, architects have started to rethink the profession of architecture. The information age brought a more complex world and hence, more complex problems with a larger number of variables than could be humanly computable. Landau (1968, p.11) wrote *"the ex-craftsman designer is faced with a new, multi-variable world in which the old delineations of the activity are no longer applicable"*. Buckminster Fuller, Frei Otto and other form finders of the 1970s pioneer interest in the potential of what materials can be. They developed a hands-off approach to design on the basis of adaptable and flexible solutions and demonstrated the importance of establishing a relationship between performance and material integrity from the early stages of design (Oxman and Rosenberg 2009). In the digital age, craftsmanship has become difficult to define. The arrival of new tools and techniques has always posed a challenge for architecture and requires a new way of thinking and doing.

Some architects associate craftmanship with a preference for the handmade over the machine-made, with a degree of 'purity' assigned to the former. This is not specific to the digital age. The tension between machine and manual production has existed since the Industrial Revolution (e.g. Ruskin's constant refusal to engage and explore industrialism considering everything out of it 'ugly' and conducive to 'ugly life, ugly things and ugly architecture' (Sennet 2009)). Middle-ground positions have been taken by thinkers and practitioners, such as Sennett and Pask. Machines, according to Sennet, can provide an insight into the thinking process by helping the maker think about what he is doing (Sennet 2009). Similarly, according to Pask and the cyberneticians, machines are tools to exteriorise and engage with the design process and processes normally internal to the mind (Steenson 2014). Lyotard (1984, p.74) reflects *"That the mechanical and the industrial should appear as substitutes for hand or craft was not itself a disaster – except if one believes that art is in its essence the expression of an individuality of genius assisted by elite craftmanship".* However, the preference for one or the other still divides architecture schools of thought, practitioners, and designers.

For others, redefining craft in the digital age means owning the entire process from design to production with careful consideration of materials and their manipulation. Clifford and McGee interviewed by Link (2016, p.1) describe: *"we are not producing a drawing and sending it off somewhere else, we are very much dedicated to owning the entire process"*; they embed material logic into their computation processes by engaging with materials in a very intimate manner, which has more in common with the preindustrial master makers than with the modern makers. For them, *"Craft is embedded in computation but also in how the material is processed. As you start to talk about materials, other logic – math, weight, structure, thermal condition – can be computed"* (Link 2016, p.2). Unlike unquantifiable craft processes, through digital tools and technologies, architects can gain a quantitative as well as a qualitative understanding of the material and their own design process.

Replicating old building methods on a large scale guided by designers' intent is another definition of digital craft. In this scenario, machines move from generative tools to becoming an extension of the hand. Designers capture the details and processes of hand-generated forms and replicate them with digital tools by using the robot as an agent in the 3D space to sculpt and paint. Parametric models that retain the relationships between objects while allowing the parameters to change and that have the ability to make bespoke elements are other notions commonly associated with digital craft (Link 2016).

McCullough (1997, p.22) defines three interrelated concepts to develop the concept of craft: *"direct experience, personal vision and mastery of a medium"*. Similarly, three main aspects can be considered central to the concept of craftsmanship in the digital age. First, reciprocal feedback loops between designers, materials, and machines where they constantly inform, define, and inspire each other. *"Craftsmanship could be said to operate on the principle of feedback, where for every subsequent step they rely on correcting their aim based on the previous result rather than a fully predetermined process. This is often described as subconscious, instinctive or experimental"* (Wiener 1950, p.102). Materials and machines become an integral part of the design process and active agents in the genesis of form, blurring discontinuities between conception and production (Kolarevic and Klinger 2008, p.120).

Second, it requires a new definition of authorship. In traditional craft, the craftsman never connects with the collective aspects of the machine. Crafts are considered to be product of individual genius (Sennet 2009). For McCullough craft means the application of personal knowledge to the making of form, the emphasis being on the individual (McCullough 1997). Digital craftsmanship cannot exist in isolation; it requires the social cohesion between human and non-human actants (Carpo 2011). The team can work simultaneously or sequentially; however, the experience is a collective one in which the different actants release and gain something. Alexander (2002), in his unravelling of the 'describable mathematical events' that underlie pleasant and beautiful things, proposes that designs are more impacted by the process than the talent of the individual designer. Materiality and appearance become linked, and design expression emerges from the *"relationship between the form and the history of its making"* (Semper 1851 cited in Lejeune and Bohl 2009, p.45). Robotics bring to architectural design the resurgence of a mass collaborative, algorithmic, architectural craftsmanship and the dissolution of authorship (Carpo 2011).

Finally, it requires the linking of different separate processes. Digital craftsmanship is not limited to novel tools and material conditions but to how new digital techniques can link processes that seemed incompatible before. Engaging with the machine and the material requires the abstraction of the characteristics of the design and a well-thought extraction of its details. This simplicity is not an easy quality and requires linking design and scientific thought processes to generate creative solutions (Cardoso 2010). The machines and the materials force the designers to take advantage of certain forms that can work better with both and that allow them to bring out the beauty of the materials and the machinic processes. Taking advantage of material properties and removing the meaningless torture to which they are now subjected is the same process for which Morris and other idealist of the crafts movement pleaded (Sennet 2009; Cardoso 2010).

3.3 Architecture Cartesian Division

Architecture since the Renaissance − and according to some authors from earlier (i.e. the twelfth century) (Lloyd Wright 1901) – has had a Cartesian division between intellectual work and manual production. During Brunelleschi's and Alberti's period, two types of models were established: one that abstracts architecture from construction and moves it away from the construction site, and an opposing more holistic model in which architects *"extend the limits of design through technical invention"* (Witt 2010, p.49). Alberti's description of the architect in his treatise *De Edificatoria* makes a clear distinction between design knowledge and instrumental knowledge, where the former defines the profession of the architect and the latter that of the builder (Witt 2010). There is a certain tension between these two ways of thinking.

For the last 500 years, the methods of designing and building have remained unchanged (Sheil 2010). Digital equipment and software during the 1990s took architecture into the virtual realm, changing the relationship between the virtual generation of architecture and its materiality (Loukissas 2012). Two divergent avenues of the visible form versus the invisible computation evolved and changed the relations between information, digital technology, architecture, and machines. A small number of architects, such as Jean Prouvé, Charles and Ray Eames and designers at the Bauhaus, disrupted this relationship and brought machines to architecture, embedded with the idea of having machines in one's atelier to test (Feringa 2015). These visionary architects reinforced the idea that while architects are not builders, they cannot remain isolated from the problem of building. They pioneered efforts in rethinking the relationship between design, materials and machines in architecture. Robots introduce a new technological possibility to architecture, a displacement that provides a new frame of reference, new expectations, and new consciousness. This new potential is not only about technology but also about changing the relationship between thinking and doing (Speaks 2011).

Baudrillard (2005) asked: How can automation be smart if it makes us simple spectators? Similarly, the French painter Villemard in 1910 depicted the construction site of the future as one where the architect is seated outside pressing buttons, while the machines are doing the work (Figure 3-1). Research and experimentation in digital fabrication seem to be approaching this scenario, moving the architect into the role of a mere spectator, an outsider button-presser (Willmann 2015). There is a need to understand the human and robot factors that enable relationships to form between them, and allow redefinition of the role of the architect in a world where computers consistently conduct higher levels of optimisation and machines are constantly capable of higher levels of complexity in materials and construction (Greyshed 2014). In particular, is important to understand the key human factors and agencies that allow the robot, in collaboration with the designer and the material, to create a difference that is meaningful. The current fascination with robots and robotic processes suggests a desire for a more holistic design approach where technical invention allows the architect to push the limits of design.

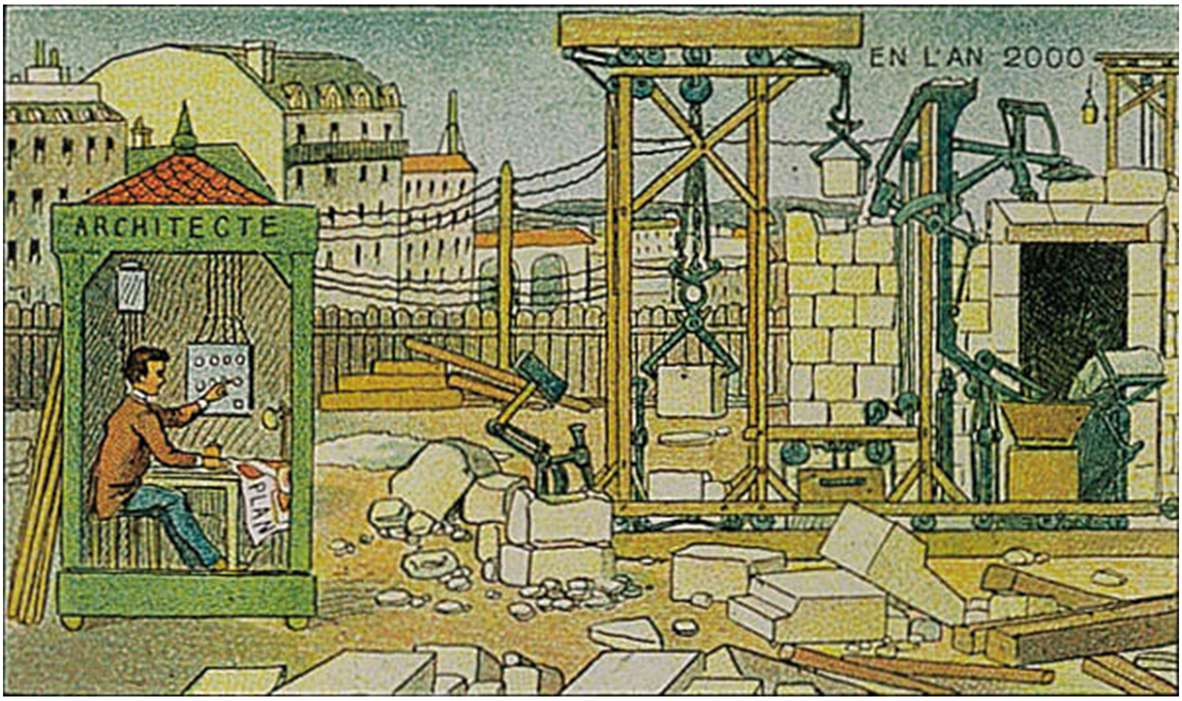

Figure 3-1 Building site of the future (2000) as envisioned by Villemard in 1901. Source: www.paleofuture.com

Architecture is going through a new phase of consolidation after a paradigm shift of how architecture is conceived and how it is produced. It includes an increase in interdisciplinary approaches, a deep relationship between architecture and technology, and an overall new era of trial and error and of prototyping in theory and in practice (Carpo 2004; Speaks 2011). This new era offers a great potential for combining computational digital and physical tools in architectural design for tasks of ever-increasing complexity, bridging the divide between digital designs and their making.

3.4 Human–Machine Symbiosis

Licklider (1960) appropriated the term 'symbiosis' in his article, 'Man–Machine Symbiosis' to human–machine interactions. During the 1960s with the advent of computational systems, pioneered by Yona Friedman and the architecture machine group, architects started to ask what it means to design and work with a computer. A machine in this context would turn the architectural design process into a dialogue, hence altering the traditional human–machine dynamic. Negroponte (1973, pp.11–12) wrote that *"The dialogue would be so intimate – even exclusive – that only mutual persuasion and compromise would bring about ideas, ideas unrealizable by either conversant alone. No doubt, in such a symbiosis it would not be solely the human designer who would decide when the machine is relevant"*. They raised questions about authorship and performance, such as who performs the design, and introduced the now familiar idea of participatory design. Computational processes started to be explored to unveil the creative potential of the computers as partners or 'consultants' in the design process (Negroponte 1969; Friedman 1980).

After an initial era of robotic experimentation in architecture, architects have gained a better understanding of the machine and material processes such that similar questions regarding the machine and its implications for the design process can be asked. The aim is to redefine the roles and skills in a design process wherein robots can overcome being used only as new building machines and become agents in a participatory design process. A human–robot symbiosis is different from the human–robot systems currently permeating architecture research laboratories and schools (Picon 2004; Gramazio and Kohler 2008; Gramazio et al. 2014). Creating this kind of interaction requires a creative design approach that takes into account the designer's needs, material criteria, and machine possibilities, particularly as it involves appropriating a machine that has neither been developed nor optimised to be used for architecture.

3.5 Dialogic Design Processes

Technology continuously shapes and adapts the physical and intellectual behaviours of biological users (Clark 2003). Clark and other cognitive scientists have made a clear distinction between what they call transparent and opaque technologies (Weiser 1991; Norman 1998; Clark 2003). Transparent technologies are symbiotic partners of humans; their level of integration has rendered them invisible in use, e.g. the wristwatch. Opaque technologies are not harder to understand, but their use does not come naturally to users and the technology, rather than the human objective, remains the centre of attention during their use. Robots in architecture have been concrete things with character, limits, and influences for the last 30 years. However, unlike other fabrication machines such as 3D printers, laser cutters, and other numeric controlled machines that are now used by students and designers almost naturally, robots have remained an opaque technology.

The cultural impact of techniques is undeniable. Humans and machines are continuously co-evolving. Mumford in his book *Techniques and Civilisation* correlates the changes in the physical environment at the beginning of the twentieth century, after the Industrial Revolution, with the changes in the mind. He rejects the idea that techniques can develop in isolation, uninfluenced by any other human desires than those from the people directly connected with their invention (Mumford 1963). The current scenario is of relatively unchanged humans interacting with robots and design technologies. Maurice Merleau-Ponty suggests that people can only incorporate instruments into their physical sensibilities through the experience of manipulating them (Merleau-Ponty 2013). Robots are more than another fabrication machine; they are versatile, flexible, highly accurate, and generic enough to allow customisation for multiple tasks (Gramazio et al. 2014). They have enabled researchers to explore and propose novel approaches to fabrication and have changed the relationship between humans and matter (Picon 2004). Therefore, the robot-augmented architect is a passenger embarking on a new journey that will generate new experiences resultant of the evolution of its relation to the physical world. Picon (2010, p.149) poses the question *"What are the salient features of this experience, how do they relate to the broader picture of an emerging new materiality?"* Robots force designers to consider external factors in design decisions in a very precise manner. If architects are going to design with robots, it is important to define the development of the human elements and the frameworks for collaboration needed to develop successful interactions between them.

3.6 Related Case Studies

The current status of robots in architecture is that of providing a new sense of 'intimacy' between the designer, his or her tools (Willmann 2015) and materials, similar to that enjoyed by painters and sculptors, yet with precise digital control. Robotic arms are increasingly being explored as design tools capable of augmenting and extending the designer's solution space to the stages of fabrication and material manipulation. The following case studies have been selected to illustrate a range of design interactions between humans and industrial robots during the design process. The interaction in each case is positioned in different parts along the design–fabrication continuum, offering an opportunity to study and speculate on different approaches to the human–robot symbiosis in architectural practice. The role of the architect throughout the different case studies is that of an active designer of the system and of the rules for the other actors to operate upon. Common across the case studies is addressing material variation as a creative force (DeLanda 2004) that allows the incorporation of differences and feedback during the fabrication stage. Studying them allows identification of the skills and toolboxes that define the new role of the architect as an active agent during a robotic mediated design process.

Establishing a dialogue between the design process and its material manifestation through robotic fabrication has been the aim of several research projects in the last few years. A live link is established between a material and a robot for real-time control with the aim to integrate material and structural knowledge into the design and robotic fabrication procedure. Lloret et al. (2014) used material sensors within a feedback loop to create a design-making process that embeds material-based observations into the robotic fabrication procedure (Figure 3-2). Schwartz et al. (2014) catalogued material behaviours throughout the fabrication process to be used later. The common thread across these studies is that most of the effort is focused on understanding and digitally simulating the physics of the material to be able to predict its behaviour during and through the design-materialisation process. Sensors and 3D cameras allow the robot to adapt to new information, but it leaves the robot relegated to the role of a sophisticated final fabrication tool.

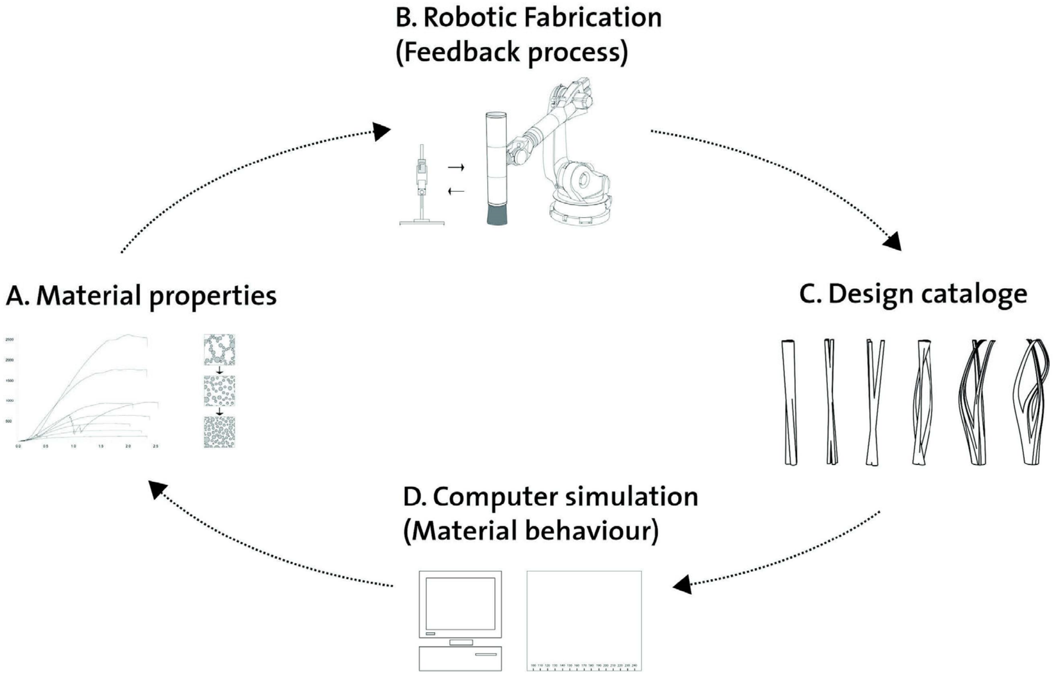

Figure 3-2 Development of robotic slip-forming based on material properties and sensors (Lloret et al. 2014).

Researchers have also explored scenarios where the designer experiences a direct engagement with the material, similar to craft processes, through robotic mediation. Johns (2014), for example, allowed the designer to produce a structurally optimised physical output from pure material manipulations by linking sensors, a robotic manipulator, and a digital simulation (Figure 3-3). Batliner et al. (2016) used the same interactive feedback loop to amplify specific design features previously defined by the designer in the software. Dubor et al. (2016) proposed a scenario where fabrication and material logic were first recorded and embedded into the robotic code. Using this information, the designer manually guides a robot through the paths while the robot maintains the particular constraints of the fabrication method. These studies transformed the robot into a mediator between the physical and the digital world, allowing the designer to engage directly with the material akin to craft processes enhanced by the ability of the computer to manage complex performance criteria in what Johns calls *"highly informed design"* (Johns 2014, p.1).

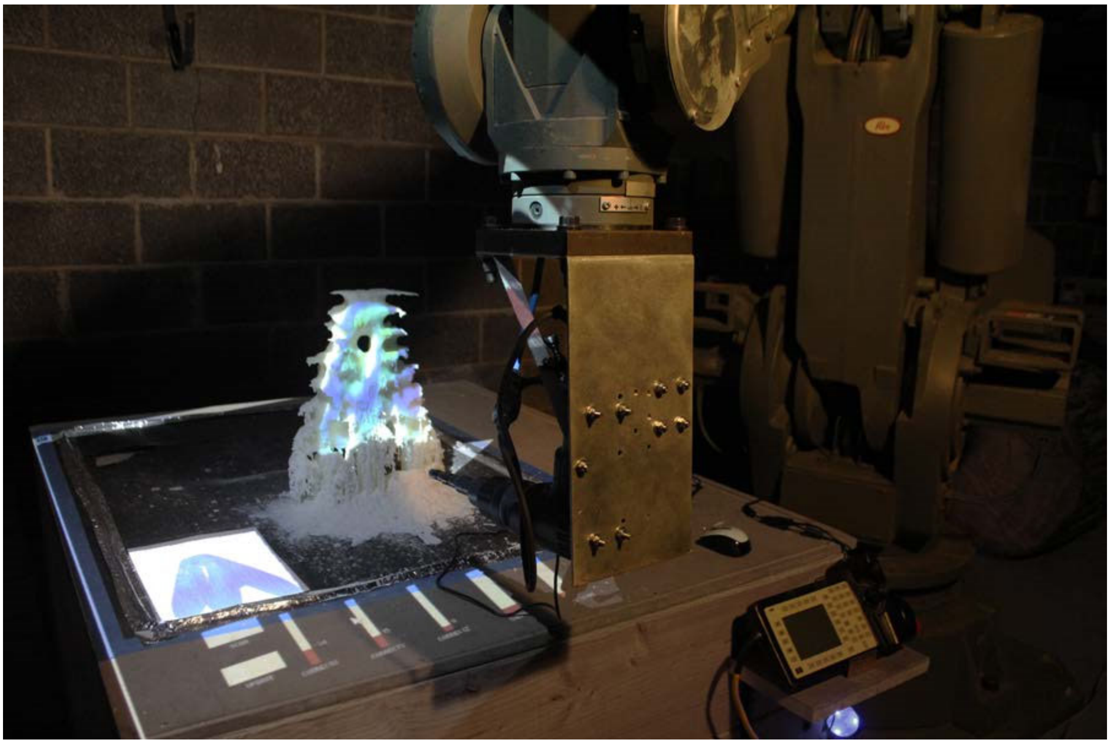

Figure 3-3 Prototype of robotic-aided mixed reality modelling by recursive wax forming (Johns 2014).

Menges (2016) introduced the concept of 'cyber-physical' to describe the effects of 'manufacturing 4.0' on the architectural domain. He defines it as construction processes in which there is a strong link between physical production and virtual computation. Examples of this are real-time sensing and behaviour-based construction processes that recalibrate continuously on the basis of *"real-time physical sensing and computational analysis, material monitoring, machine learning and continual (re)construction"* (Menges 2016, p.32). This is in contrast to traditional construction processes which rely on explicit instructions. An example of a practical application of this concept is the 2014 ICD/ITKE research pavilion in which an industrial robotic arm wove a carbon fibre compression shell inside a pneumatic bubble that acted as the formwork (Figure 3-4). The robot was constantly adapting its weaving paths to the changes in the environment of the pneumatic bubble. Augmenting robotic processes through sensors and feedback loops enables the integration and linking of the physical and the digital domains.

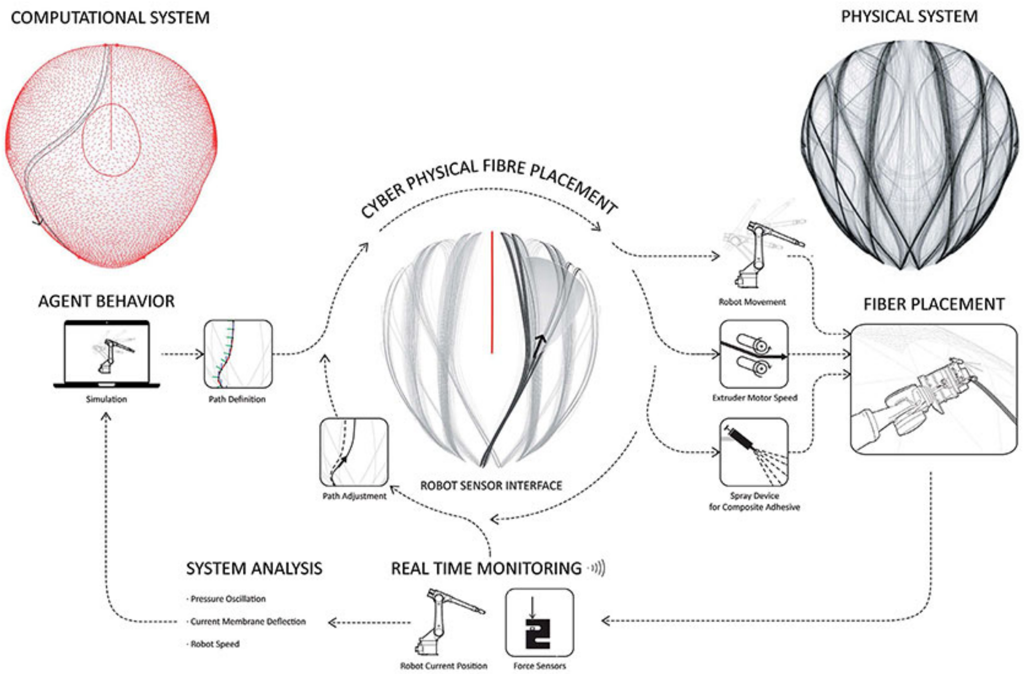

Figure 3-4 Cyber-physical robot weaving. Source: http://www.achimmenges.net/?p=5814

Another approach is to use machine learning to embed craft knowledge into the robot for its path planning decisions. This includes the analysis of actions such as those from a carpenter for wood carving (Brugnaro 2017) or from a stonemason (Steinhagen et al. 2016). Common amongst these projects is the idea of establishing a direct link between physical material manipulation tools and machine intelligence by training the machine to replicate and eventually augment the actions of the human.

Industrial robotic arms are being used in these projects and are also starting to influence how the projects develop. Technologies, when they mature, start to understand the constraints and thus abstract and reinterpret the problem to finally create their own language (Bonsignorio 2015). With the use of new material technologies and new processes, a new robotic language is starting to develop in architecture: a language of its own that is not copied from previous pre-robotic era constructs. Architects are starting to accept and incorporate the language of the robot in their creations. The Venice Biennale entry in 2012 ‘Arum’ (Figure 3-5) from RoboFold and Zaha Hadid Architects is an early example of such collaboration. An existing metal folding technique was robotised and enhanced by a robotics company. This technique has a specific aesthetic associated with the product of the machine and the material capabilities. Instead of imposing its own aesthetic, the architect adopted the aesthetic of the robotic process and worked with it to arrive at a joint design solution that created a new aesthetic product of the machine and the designer (Epps 2014). Similar to craftsmanship processes, where information from the material is inputted into the design, we are starting to see designs that are informed by the material properties and a deep understanding of robotic processes.

3.7 Agencies in the Design Process

Agents or actants as defined by Callon and Latour (1981, p.286) are *“any element which bends space around itself, makes other elements dependent upon itself and translates their will into a language of its own”*. More importantly, agents make a difference to each other by their relations. The following agencies are identified in a human–robot design team. A description of the agents and their potentiality is presented before any relationship is formed. This dissertation concerns itself with human, material, and robotic agencies. It is important to note here that while human agency is defined through cognitive and behavioural processes, material and robotic agencies are derived from the set of potentials and limitations embedded in each. A future may be anticipated were machines are artificially intelligent, but even in present times, the aforementioned physical characteristics allow robots and materials to inform, amplify, and limit choices and decisions and thus can be viewed as appropriating agency from the human operator.

Figure 3-5 Robotic folding process of pieces for 'Arum', Zaha Hadid Architects (Epps 2014).

3.7.1 Robotic Agency

Designing and using robotic agency rather than using the robot as just another fabrication tool requires an introduction of scientific rigour to the design process; a holistic approach to architectural design that considers adaptivity; a set of organisational principles, material, and machinic processes; and a mutually formative relationship between cultural and technical aspects. This implies the introduction of a technological basis for architecture, which has remained relatively elusive when compared to other disciplines (Willmann 2015). Using a robot forces architects to think systematically about what they are doing and to mechanise the complexity of craft and other manual tasks, which are normally taken for granted.

The role of the robot in architectural design processes is still ambiguous. The design process, unlike the fabrication process, is an enquiry process without a defined solution. Three scenarios are envisaged, which through feedback loops can enable different degrees of robotic participation in the design process:

- As a **slave** to the designer's wishes, as can be seen in most robotic applications in architecture today in which the robot only obeys human orders;
- As an **amplifier** that does not simply replicate the designer's wishes, but can elaborate upon them and contribute technical expertise towards the design intentions (Negroponte 1973). This would be a man–robot symbiosis: the robot would guide the designer's decision-making according to a complex set of local and global criteria that might have been ignored otherwise (i.e. it can perform structural analysis on the material, as it is being form found and feed this physical information to the designer before he or she continues the exploration process); an example of this would be 'mixed reality modelling' by greyshed (Johns 2014);
- As a **coordinator** or **oracle** where robots make alternative decisions in human situations, specifically in situations that are difficult for humans and when they can have greater degrees of accuracy in their answers (Bostrom 2014). Robots can have a more comprehensive perspective, using their computing ability to process large amounts of information (Lem 2014). In this role, the robots only provide advice, and it is the humans who make final judgement calls: this perspective merges the computing strengths of the robot and the perceptive strengths of the human. The robot guides the way, but humans have the final call. In this scenario, unlike in the previous one, the robot has information about the design objective and guides the human towards it. The robot will indicate when actions are not in the desired direction and will provide advice.

However, the robot's roles are not fixed or unique. Researchers on HRI have found the best results occur when the boundaries between the robot's role and its levels of interaction are fuzzy (Scholtz 2002a). The coordinator robot can take on the slave role at some stage during the task if it is more efficient than a hand-off to the designated human team member. A team member can also command the robot and take on the role of coordinator if the need arises during the task. Additionally, in larger team configurations, all of the robot's roles can occur at the same time with the same or different human team members. Different technologies and feedback mechanisms need to be enabled to support these multiple interactions and robot roles. Additionally, different information and modes of interaction are required from the robot for the users in each role.

RAD aims for a scenario in which robots enhance human creativity by giving designers an insight into their own creation and materialisation process. By exploring these roles, the designer can unfold the possibilities and qualities latent in the engagement with this tool and technology (Kolarevic and Klinger 2008). The focus shifts towards the design process and the different ways of thinking and making that it enables. Designing with robotic agency explores the possibility of enhancing perceptibility of the physical through digital intelligence (Ayres 2006), hence augmenting and enriching the design process. The robot can become a collaborative partner that augments the designer's capabilities through its computing capabilities, range of movements, ability to allow geometric flow between the digital and the physical design, and flexibility given the number of end effectors that can be developed and attached to it.

3.7.2 Human Agency

"It's always been an illusion that we have complete control. Architects need to get comfortable in creating the conditions for things to happen and thinking of things in ranges rather than precise outcomes" (Benjamin 2018).

Humans are immersed in the physical world, but the boundaries between the human and the physical are contested. It could be argued that human limits are 'the skin and skull' (Clark 2003). Clark argues that some technologies have become so embedded in the human biological system that the human brain and its problem-solving mechanism are just the composite of biological and non-biological tools: *"Various kinds of deep human-machine symbiosis really do expand and alter the shape of the psychological processes that make us who we are"* (Clark 2003, p.32). The concept of 'human' is flexible and in constant flow. Human agency can be regarded as a subjective, first-person perspective on one's way of reacting and acting within the world (Malafouris 2008), by using the technologies available.
Professional identities in architecture are diverse and dynamic. The role of the architect has varied throughout history, from that of the poet master-builder that frames all other arts inside

his edifice (Lloyd Wright 1901) to that of the virtual-master being recognised and acknowledged through objects that exist only on the screen (Loukissas 2012). The boundaries of architecture are continually shifting (Schon 1984). A comprehensive, traditional definition will be that of the architect as a ‘generalist’ who needs the capacity to deal with and negotiate amongst different specialists, consultants, and clients, and achieve sufficient understanding to allow the execution of a design vision. Computers have become central to the architectural workflow increasing connectivity and enabling collaborative modes of practice between architects, engineers, and specialists. Additionally, they have further blurred the already ambiguous boundaries that separate architects from engineers (Loukissas 2012) as both now use the same simulation and coding tools. As the divide becomes unclear new common fields for negotiation and discussion are created. Digital technologies and geometric modelling further challenge traditional views of architecture as an unmediated representation of the will, knowledge and intuition of the architect. They redefine the traditional master-apprentice relationship considered central to architectural practice and to design education (Schon 1984; Cuff 1992; Picon 2010).

3.7.3 Material Agency

Material agency is a concept introduced by Lambros Malafouris in his essay ‘At the potter’s wheel’ in which he challenges previous anthropocentric notions of agency by defining it as follows: *“If there is such thing as human agency, then there is material agency; there is no way human and material agency can be disentangled”* (Malafouris 2008, p.22). He goes on further to describe material agency as something not inherent in the material itself but as a relational, emergent property that develops through engagement with the material (Nahmad Vazquez and Jabi 2016). This continuous dance of agency, which can be seen in craft processes, results from the coupling of mind and matter.

Picon (2010) describes a similar notion of materiality which is something not related to the material but to the relationship that humans have with the physical world. Materiality becomes the relationship between the material world, matter and humans, and it involves the cultural process of perception (Picon 2016). He goes on to further contend that in order to define the material and hence the ‘non-human’, we have to first define the ‘human’ (Picon 2010, p.146) by defining boundaries they can start to cross. The concepts of material agency and materiality have recently entered architectural discourse (Picon 2004; Gramazio and Kohler 2008; Oxman and Rosenberg 2009). Alberti once said that *"It is entirely possible to project whole forms in the mind without recourse to the material"* (Alberti 1988, p.5). The digital is changing materiality, and questioning co-constructs between matter and humans. However, it is not the definition of matter that is changing, but the understanding of the relationship between human and non-human through the digital.

In architectural practice, materials have traditionally been used to construct a built version of an idea that was determined in advance. Additionally, designs usually follow their initial path, disregarding any information that the material might have been trying to add during the formation process. This has resulted in a linear, unidirectional flow of information from the design model to the code to the robot (Bechthold 2010). Carpo (2003, p.465) established *"If we design buildings prior to building them, we can only build what we can measure"*. New developments in 3D scanning technology have made movement between the digital and the physical easier. These applications allow better and faster analysis, simulation, and experimentation with material properties, and new material configurations, rendering computation and materiality inseparable (Picon 2010). By giving us a deeper understanding of material behaviour, they allow the consideration of craft as an approach to making rather than as a specific way of making (Sennet 2009). In this context, craft and material agency refer to the form being developed, following a deep knowledge and understanding of the potential of the material rather than it being conceived by the architect and then imposed on passive matter, just as in the pre-digital era (Protevi 2005; Kolarevic and Klinger 2008).

3.8 Feedback in the Design Process

Feedback is the only way that the machine can have any type of communication with the outer world; otherwise, it is only executing preprogramed sets of inputs; the division between body and mind does not get blurred; and the past activities of the machine will have nothing to do with its future activities. The robot as a design partner needs to accommodate change and variation. Feedback between the analogue parts of the process and the digital ones becomes important.

Human–technology relationships are mostly unidirectional. They tend to prioritise human element behaviours over technological ones. However, only through feedback loops and recursive, bidirectional flows of information between the human and the non-human can relational meanings emerge (Berscheid and Peplau 1983). When humans relate to each other, different types of meanings and emotions can emerge from these human–human relations (e.g. attachment, advantage, and commitment). Once this relationality is formed, both agents influence and impact each other and form a relationship (Harvey and Pauwels 2009). Feedback gives the robot the potential to respond to the human and enables bidirectional exchanges. It allows for the connection between the designer and the robot to become a relationship. The robot moves and interacts in the physical world, generating feelings and emotions in the humans which they then describe in biological terms. This gives the human–non-human emergent relation the potential to become a social relationship by embedding in it a subjective meaning

A traditional issue in HRTs is how the human gets feedback from the robot regarding either its understanding of the current situation or the actions that it will undertake (Scholtz 2002a). In human–human teams, this happens by body cues, communication, and simple observation. A considerable amount of research has been conducted on finding ways for robots to present information and feedback to their human partners (Breazeal and Scassellati 2002; Bruce et al. 2002). The rationale being that regular people should be able to understand and interpret the information that the robot is communicating. Robots as teammates in the architectural design process have the advantage that computers and 3D representations are central to the architectural workflow. Architects, through computers, have increased their connectivity and adopted collaborative modes of practice that blur boundaries between architecture, engineering and specialist domains (Loukissas 2012), as all of them now use the same simulation and coding tools.

Additionally, feedback is implemented with the purpose of analysing the results of the robot's latest actions and their effect on the material which can then be used to determine the following actions (Raspall et al. 2014). Thus, the conventional unidirectional workflow from 'digital design' to 'physical production' becomes an iterative sequence that allows the designer to make adjustments on the basis of more complete information within the design environment enabled by the robot. The design process enhanced by robotic and data-integrated techniques will be a hybrid of human and non-human elements where the boundaries between human and machine capabilities are frequently contested and always negotiable.

3.9 Human–Robot Design Teams

In a human–robot design team, although team members are called peers and teammates, it is not suggested that humans and robots are equivalent in terms of their skills (Scholtz 2002a). Each team member contributes with different skills and abilities, but their agencies and contributions towards the team and its goals can be considered equal (i.e. the influence that they have over the team and the network that forms will be different given different actors). However, humans retain the ultimate control irrespective of their position and that of the robot (slave, coordinator, or oracle) within the team. The robot as a design partner might not need to be comparable to a human design partner. It has its own characteristics and behaviours that complement and aid those of the human. Robots will need their own denomination as collaborative partners, which should not be interchangeable with that of their teammates. A robot partner needs to be evaluated with a different set of criteria from that used for a human teammate (Groom and Nass 2007). They can become partners in new roles that are needed within the design process but do not exist as yet.

3.10 The Robocrud

'Cybercrud' is a term coined by Theodor H. Nelson in 'The crafting of media' that refers to putting computers over users by saying 'the computer has to have it that way' when perhaps a similar thing can be programmed or done in a very different way. *"As we learn to distance ourselves from 'cybercrud', the question becomes not, 'how do I relate to this sinister demanding artefact?' but 'What is the grooviest way to use this thing?'. The human* *environment can now be wholly, wonderfully redesigned"* (Nelson 1970, p.17). Robotic processes in architecture can be considered to be in a 'robocrud' moment where they are not easily understandable nor relatable for designers not trained with them. They present the designer with limitless ideas that stretch in every direction rather than a system that helps the designer organise and understand his or her world. For robots to permeate into the architectural discourse at a deeper level than that of highly sophisticated fabrication tools, they need to become environments that augment the designer and transform the creative process by enabling new dialogues and collaborations. Understanding the key human factors that shape human–robot design interactions can enable robots as holistic environments in which the different agencies of the design process develop.

3.11 Redefining the Design Process

Negroponte and the cyberneticians of the 1960s redefined the design process as a decentralised process, where the architect is no more the centre of the design and the design problem is described in logical terms that can make sense for the computer (Steenson 2014). The proliferation of computers made this new definition and design process widely accepted. Robots support a new multidisciplinary approach to design encouraging architects to work directly from the early stages with other disciplines (e.g. engineers, materials scientists) providing a more holistic approach to design. They allow architects to mix craft and tools in intellectually meaningful ways, creating a trinity of material, technology, and form (Lynn 2008). Robot–human collaborative design scenarios are more difficult to envision and deploy than robot–automation ones. Design strategies that choreograph interaction, hardware, software, and environment with one another are needed. Design would result not from the superiority of one of its components: material, technology, and form – but as an assemblage of sequences that are modified by their mutual presence.

RAD aims for a deeper unity achieved through the interactions of the different agents and processes where the position and influence of each is defined and determined, allowing for variations in their output. Form in this new agenda is not separated from the process of formation but shaped by fields, forces and agencies. RAD demands greater thinking needs from the architect, as he or she does not only need to create the design but has to do it in a systematic and machinic way. RAD allows architects to engage not only with the materiality and manufacturing issues but also with the information that underlies the process.

3.12 Shifting the Agency Model

The use of novel digital technologies in architecture represents a challenge to the traditionally accepted divide between *"two cultures"* (Snow 2012) or two ways of thinking: the qualitative culture generally dominant in the arts and humanities and the quantitative culture usually related to science and technology. The architect needs to start from an understanding of design and making, negotiating and merging them into a holistic process in which the division between one and the other is no longer visible. This leads to the creation of an architectural process that regards robotic technology not only as another production medium but also as its cultural interface (Willmann 2015).

RAD requires a broad view of how robots affect the design system and its relationships. It requires integrating the parameters and principles of the robots with material intelligence and human agency. Robotic design allows the designer to get *"closer to the analogue and material world by mastery of the digital world"* (Sheil 2012, p.140) through an iterative process between the two worlds. It establishes a new paradigm in which a deep crucial relationship between architecture, technology, and its physical materiality is enabled by new modes of machinic thought. The architect becomes a designer of processes and interfaces between the virtual and the physical, and an editor of the constraints governing their interactions. The robot becomes the coordinator that can oversee the entire project, guiding the process of formation, in which the architect makes the final judgement calls.

In a world where the genesis of architectural design is digital, robots can offer architects the opportunity to explore the physicality of their designs from early stages. Architects can experiment and transfer design ideas to the physical world by using the strengths of the robot, such as its strength and precise manipulation of the physical object. The architect brackets the realm of possibilities by embedding design principles in the material and using constraints that open new possibilities during the formation process. Matter and material behaviour are implicated in the geometry itself (Reiser 2006). 3D scanning technologies, robotic vision and sensors allow immediate, accurate feedback. In this scenario, robots do not only redefine the design process but also the hierarchy of the building parts and their meaning.

As the new architectural process finds its place, the other agencies involved in the design and building process will adapt. Architects will have to find which sphere they can occupy in this new ecosystem of tasks and agencies. In the current state of robotics in architecture, architects are conducting research on materials, robotics and geometry, and are designing their interactions. This situation will not continue indefinitely. Other disciplines will have to find their roles, and the robotic process will need new expert roles to be created at each stage. Architects will need to reframe their work and skills around these new agencies and negotiate their technological moment, which is changing the human–machine–material relationships. Similar to the revolution initiated by computers when introduced to architectural practice, the profession has largely never looked back (Cecchi 2015). The new machine suggests now as it did then: *"a new range of forms, new ways of knowing and new kinds of professionals in architecture"* (Loukissas 2012, p.67).

'Strange Strangers' is how Timothy Morton describes the relationships between entities. He says that the information at the moment of interaction between agents is always incomplete, suggesting that the outcome will always be unexpected (Morton 2012). Designers like to design and to be in control of all aspects of their creations. A shift in the agency model encouraged by new digital technologies requires the designer to relinquish some of his or her unidirectional control and to allow the unknown control of matter to develop during the process of becoming (Pickering 2011). This process raises questions of authorship. A new mode of non-authorship should arise similar to that of Gothic cathedrals, where the interaction between the agents was paramount. Novel hybrid-agency models will be required, in which the architect becomes an active agent through the materialisation process and diverse agents have equal influence on the final design (Carpo 2011).

RAD will become a new synthesis for the various processes of an augmented architect. Architecture can find in robots a reconnection to the physical world. The challenge now is to deal with the human factors that have to be considered for this connection to be successful and have an impact. An essential component of the current architectural agenda is to define the shifting boundary between digital simulations and physical realities. At this intersection, strange things might occur, but they will allow definition of how the transition towards an enriched reality will enhance design and architectural practice. It will allow the emergence of new design procedures that can deal with the complex interactions between the different digital, human, and material agents. A robot–human–designer feedback loop changes the notions of materiality. It allows architects to address physicality in a different manner; just as automobiles changed the perception of the city and augmented human senses, robots add another layer of senses and perceptions to the human ways of seeing, feeling, and understanding the world. The use of the robot in design, while allowing different ways of feeling and thinking about the physical materiality of the world, also needs new ways of representation and design thinking.

Chapter 4 KEY HUMAN FACTORS: DEVELOPMENT OF A THEORETICAL FRAMEWORK FOR HUMAN–ROBOT COLLABORATIVE DESIGN

4.1 Introduction

This chapter presents a theoretical framework of key human factors at an individual level that influence the development of team fluency in a human−robot collaborative architectural design team. The identified human factors that influence team fluency will be tested in part two of this dissertation through an architectural design case study.

The breadth of work aimed at developing collaborative and, specifically, collaborative industrial robots has been described in chapter 2. Industrial robotic arms are a relatively recent introduction and rapid advances have been made allowing their adoption in the field of architecture. However, the work to date has been mostly focused on developing fabrication and material protocols appropriate for robots in architecture. Daas (2014, pp 623) declares *"a lion's share of literature in the field is dedicated to robots for fabrication"*. Identifying that a tremendous effort has been placed on understanding technical aspects, such as machine layout, code generation and material behaviours. Although more work is starting to be directed towards developing human–robot interfaces, including those using augmented reality and virtual reality technologies, to enable direct robot control and creating easy and intuitive robot interfaces (Johannes Braumann 2017; Nick Cote 2017) the focus remains predominantly on the technical aspects of the collaboration. Human factors, which are key to enable the successful implementation and further adoption of a design robotic partner within the designer environment, are often neglected.

This chapter discusses the relevance of including the human element during the introduction of new technologies. It develops a theoretical framework under the concept of team fluency for human–robot collaborative design teams and defines its constructs. The theoretical framework is based on key human factors that have influenced the successful implementation of HRC in the literature in comparable and relevant domains. It is important to note that HRC in the case of industrial robots is a nascent field and applications are limited. The fields where HRI metrics have been more developed and tested are search and rescue operations, structural evaluation, medical assessment, command and control and logistics (Singer and Akin 2012) using robots which have a different set of characteristics from those of industrial robotic arms. However, the metrics are not sufficient to understand team performance issues during design activities. Human–robot teams are generally focused on finding the correct solution to a problem in a defined space (i.e. military mission, health care assistance) whereas design tasks are mostly concerned with exploration in a vast design space where there is not a single correct solution.

The review of all of these fields provided a large collection of literature to identify the factors most relevant to HIRC in the design activity and from which the theoretical framework for team fluency was constructed. Key human factors in these domains were identified with their evaluation scales, and appropriated when relevant to the domain of industrial robotics or to that of creative tasks.

4.2 The Importance of the Human Element

As robots leave laboratories and specialist domains (i.e. military, manufacturing) to embed into more processes of human life; It has become evident that robots can augment, supplement and improve human performance on tasks. However, the adoption and implementation of HIRC, unlike the adoption of industrial robot arms, represents a radical technological change that augments the designer both digitally and physically and changes the traditional relationship between both aspects of the design activity. The successful implementation of a radical technological change, like this one, is not only a technical challenge but also a human one. HIRC in the design activity represents a change of the agency model and requires the acceptance of non-human actors as active participants and team members that not only work in the same space but also interact and are active participants during the development of the design idea.

Historically, the introduction of new technologies with inattention to the human factor during their implementation can lead to excessive workload demands and changes to the human activity that lead to performance errors and opposite results from the expected ones (Singer and Akin 2012). An example of this is the ‘longwall’ introduced in the 1950s to improve coal mining. The longwall aim was to improve coal mining by introducing automated blades that sliced the coal and transported it to the surface. The method which was intended to increase productivity resulted in miners no longer working as a team and becoming spectators who watched the process. Physically and intellectually their work was less demanding but the productivity also became lower and the workers’ stress levels higher. The effects of the longwall method, although almost seven decades old, are of historical relevance and still provide a good frame of reference on how new technologies that do not attend to the human factor can have negative effects and great social and psychological consequences such as the break-up of teams and higher stress levels (Trist and Bamforth 1951).

The manufacturing industry, which has used robot arms for almost six decades, has faced similar problems when introducing industrial HRC systems. Sheridan (1997), on his major survey of manufacturing organisations, concluded that inattention to human issues is the major barrier preventing the successful introduction of collaborative automation systems (Ghani and Jayabalan 2000; Waldeck 2000; Lewis and Boyer 2002; Charalambous 2014). This implies that in order for a new technology to be supported and accepted by human’s significant attention needs to be given to the human factors, concerns and expectations (Park and Han 2002; Fraser et al. 2007).

Although activities using robot arms in the manufacturing industry cannot be directly interpretable as design activities, design is not fundamentally different from other collaborative activities (Jabi 2004). The main differences are that the design process is non-linear, multidisciplinary and does not have a single correct solution but a ‘solution space’ of multiple possible, viable solutions. Donald Schon (1988) defines the design process as a dialogue mediated by the designer artefacts and the design situation. For robot arms to become collaborators in the design process, it is crucial to understand the human element, and the design and social challenges occurring due to the incorporation of a robot partner.

4.3 Theoretical Framework

To understand how designers, relate to robots and how the human−robot design team operates and its strengths and weaknesses various factors have to be taken into account. These include the team, the task, robot, human and environmental factors. The design and evaluation framework for designer−robot collaboration is tested under the overarching concept of 'team fluency'. Fluency is a trait of a team that cannot be displayed by individual team members (Larsen and Shore 2018), hence its selection as the underlying criteria to evaluate HIRC.

The chapter first defines the team, its taxonomy and configuration. Four evaluation factors have been identified as the main components that determine fluency in a team: trust, collegiality, improvement and robustness. These four main evaluation factors are described and split up into several indicators, which are extracted and justified by the literature and research in the fields of human–robot interaction (HRI), human–robot collaboration (HRC) and human–computer collaboration (HCC). The term human–industrial robot collaboration (HIRC) introduced earlier, and which is more appropriate for this dissertation, is used.

4.3.1 Team Fluency

Team fluency is defined as the ease of collaboration between the designer and the robot. It is the perceived and shown lack of friction between the different agents throughout the design task. Fluency in a joint action is a quality of agents performing together and adapting and coordinating with each other in an adaptive way. Fluency is a quality observed in a variety of human behaviours and recently, in the last ten years, has started to interest researchers in the area of HRI. However, it is worth noting that researchers in the last decade have not come to an agreement of what constructs fluency in HRC, hence it remains a vague and ephemeral concept. Nonetheless, it can be contended that fluency is a quality that can be recognised in a team and assessed when compared to a non-fluent scenario. A fluent teammate evokes appreciation and confidence (Hoffman 2019). Hoffman (2019, p.01) describes *"if robotic teammates are to be widely integrated in a variety of workplaces to collaborate with nonexpert humans, their acceptance may depend on the fluent coordination of their actions with that of* *their human counterparts"*. Researchers have tried to relate fluency to efficiency (Hoffman 2013b; Hoffman 2013a), however they have found that both are not correlated. Participants would rate their experience as more fluent, even when there was no difference in efficiency of task completion (Hoffman and Breazeal 2007). This suggests that fluency is a separate feature of a joint collaborative activity which requires its own separate metrics (Hoffman 2013b).

This research contends that fluency is a quality that can be positively assessed by analysing the individual components that facilitate team collaboration. By exploring the features that make fluent teams the aim is to propose a framework to evaluate fluency in a design HIRC task and help inform the future design of successful robotic teammates. The main fluency parameters are further subdivided into specific aspects, including subjective and objective metrics. These are then evaluated through questionnaires, field notes, videos and semi-structured interviews; the last three are specifically important to capture the qualitative notions of fluency in a collaborative task. Studies on the field of HRI have shown that when evaluating fluency, it is important to identify the fluency that is perceived by a bystander watching the collaborative interaction from the fluency experienced by the human participant in a human–robot team (Hoffman 2013b) *"participation is more sensitive to fluency than observation"* (Hoffman 2013a, p2).

The concepts indicated below are the parameters based on the literature, which have been used to measure different key human aspects of fluency in a team (Figure 4-1). They confirm the basis for the development of a successful design HIRC. The lack of current guidelines and parameters to evaluate successful HIRC in design tasks makes a need for this research to describe these parameters in detail.

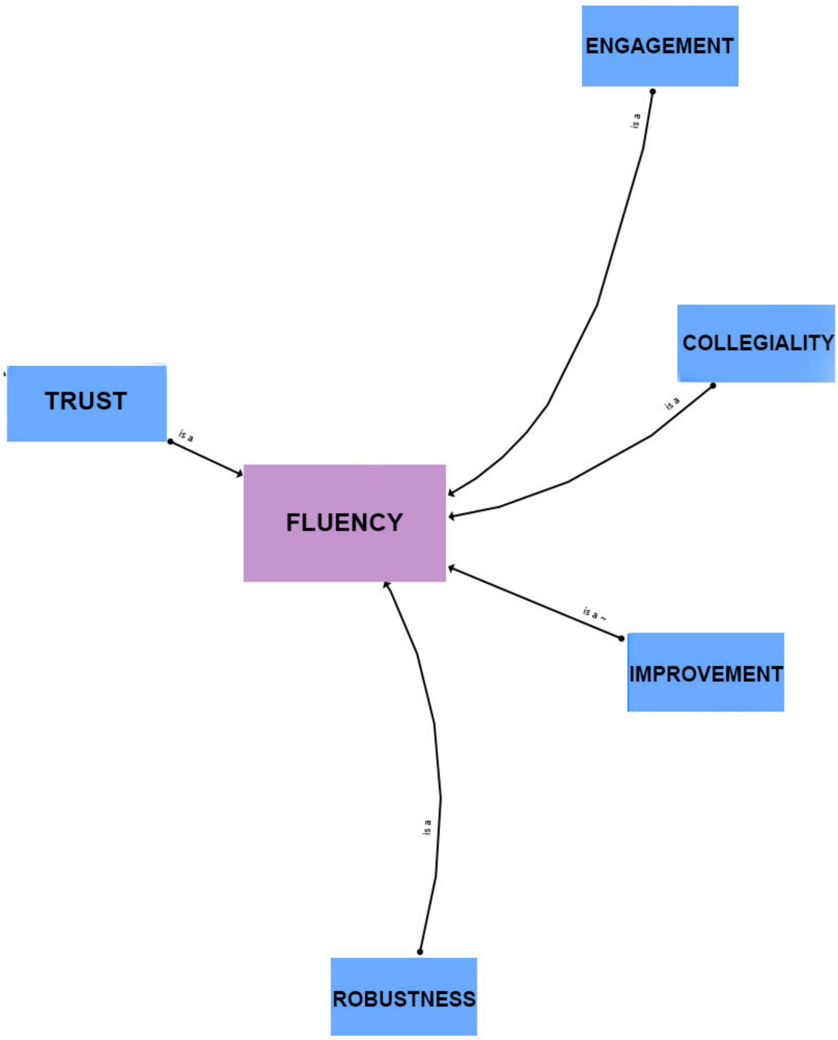

Figure 4-1 Main constructs of team fluency.

Trust and the parameters that compose the measure of trust make half of the assessment scale to evaluate fluency in the human–robot design team (Figure 4-2). The requirement for trust is crucial for successful teamwork (Hinds et al. 2004; Charalambous 2014; Charalambous et al. 2016).

The following sections first provide a description of the concept of a team for this study. Subsequently, they describe each of the notions considered in the framework to evaluate team fluency on design HIRC tasks.

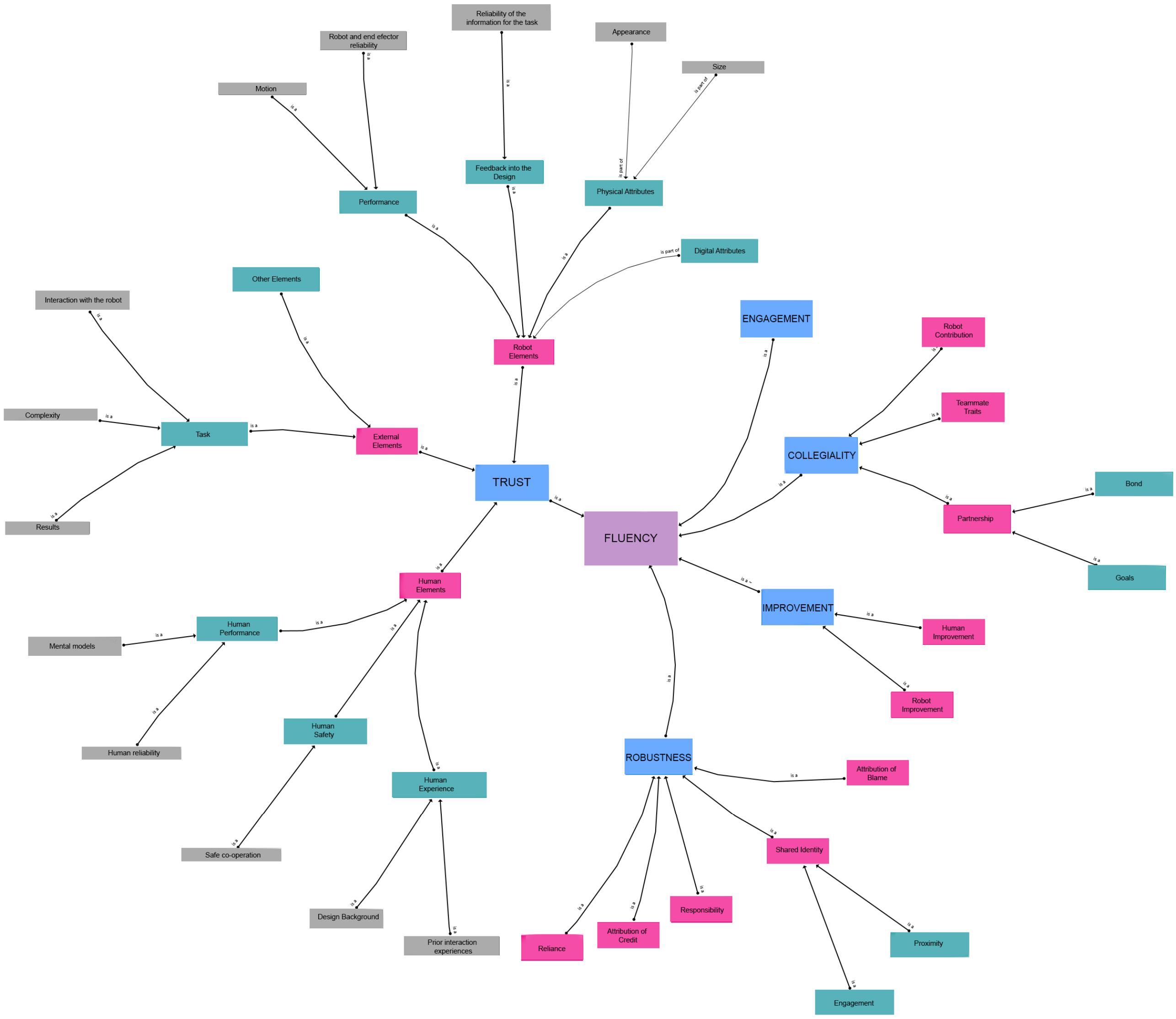

Figure 4-2 Team Fluency full map of themes and sub-themes. The left side corresponds to the sub-themes of trust and right to sub-themes of the improvement, collegiality and robustness constructs.

4.3.1.1 Defining a team

It is crucial to define the concept of a team, the team division and task assignments before establishing the parameters to be studied on the HRT. A team can be defined as a system where its behaviour and models arise at the interactions between the actors within the team. Teamwork is defined by the dictionary as *"work done by several associates with each doing a part but all subordinating personal prominence to the efficiency of the whole"* (Merriam-Webster 1828). Teams have become the most successful, powerful and effective social structure for humans (Cohen and Bailey 1997). They promote a sense of identity, mutual dependence and emphasise similarities and shared goals (Groom and Nass 2007).

Both team structure and task assignment have consistently been shown to influence how team dynamics develop and evolve (Macmillan et al. 2004). Team structures are scenario specific and depend on the task characteristics and resources available (Macmillan et al. 2004). There are different organisational models for teams; the most used ones are:

- Functional teams in which the operators are specialised and have rigidly defined roles and responsibilities (e.g. one person is responsible for searching, the other one for attacking). Functional teams perform better on predictable tasks.
- Divisional teams in which tasks are self-contained. Each team member is allocated resources to complete their task (e.g. a company with several product subdivisions. Each subdivision is responsible for all aspects of its product from research, design to marketing, etc.). Divisional teams have a higher response rate and perform better when the level of uncertainty in the environment and the task is higher as the task is self-contained (Galbraith 1974; Macmillan et al. 2004; Gao et al. 2016).

Different team structures would offer different advantages depending on the task and the environment (Gao et al. 2016). The current design scenario and the characteristics of the design task are better suited to a functional team structure. Specific task roles are assigned to the robot that rely on its characteristics, such as precision, information processing etc. and design decision-making is assigned to the humans. The robot goes beyond being a tool by offering feedback, suggestions and information to which the designer can relate. Literature on HRT has been discussing whether the robot should be regarded as a team member or as tools to be used by humans (Groom and Nass 2007). Researchers argue that until advances in robot autonomy and intelligence are manifested in unstructured field conditions, the concept of the HRT is a matter of phraseology to refer to humans and robots interacting together as teams or to people using robots as a team resource or tool (Groom and Nass 2007; Gao et al. 2016).

Belief in the concept of a team

In order to form efficient teams humans need to believe in the concept of a team, that there is a benefit in working together with others and that they can achieve better results as a team than if they work on their own (Joe et al. 2015). *'Team Orientation'* is a term coined by Dickinson and McIntyre (1997) to describe team members' positive or negative attitudes towards each other, the team leader and the task. Team orientation will define individual belief in whether it is worthwhile to stay in the group or leave it. There are only specific circumstances that will encourage people to work as a team. The work of Larson and LaFasto (1989) explains a range of these circumstances, which include situations in which there is a clear, higher goal that cannot be achieved without the coordinated efforts of various individuals. When circumstances are not met, the performance of the team will be below expected levels and the team is most likely to encounter problems working together (Joe et al. 2015).

Social factors defining team performance cannot be translated to apply to human–robot teams. Robot agents and general automation will work towards the task goal without being affected by a belief in the concept of a team. Moreover, robot agents do not have beliefs, sense of responsibility, conflict resolution skills nor a need for social acceptance (Joe et al. 2015). Hence there is a need to explore new protocols on task assignment, communication flows and how interactions are defined in order to establish human–robot design teams, understand their formation and behaviours and evaluate their performance. For example, communication, which is considered central to team behaviour and for team members to engage and function as a team, cannot work in the same way in human–robot teams. Communication does not usually flow naturally between humans and automation as it does between humans, and computer interfaces can be relatively clumsy. Understanding what and when human designers expect the robot to communicate become crucial for the design of the team structure, the task and collaboration.

Team structures are particularly relevant and attractive to humans. In contrast, the number of animals that believe in the concept of a team is rather limited (Dawkins 1976). Animals and other species would establish social structures according to the species-specific strengths and weaknesses as a means to achieve their goals (e.g. geese flying in a 'v' formation changing positions and pushing the weak birds to the outside, in an 'every bird for itself' strategy with more effective results than trying to communicate and support each team member)(Wilson 2000). In order to allow human–robot teams to be successful it is crucial to make an effort to avoid being blinded by the human tendency to see '*humanness'* everywhere and try to impose models of robot–team interaction which are only suitable for human–human teams. For robots to be teammates an HRT structure needs to be designed where they complement each other while allowing novel social structures to emerge that are different from those under the traditional concept of teammates. Traditional human team structures cannot provide a comprehensive framework to include this new kind of teamwork. Appropriate evaluation benchmarks need to be established during the design of the team and the collaboration that allow for robots to succeed as teammates while fulfilling human expectations and beliefs in the team structure.

Team leadership

Good and strong leadership is a crucial component in effective teams. This can be achieved by either formally appointed leaders or emergent informal leadership by the team members (Larson and LaFasto 1989). As robots move from operators to collaborators and become smarter their position within the team will change, affecting and changing human performance. They would allow for a team structure and its definition to become a flexible variable and remove sequential dependency and human leadership. It could be argued that increasing robotic agency could be a positive thing that encourages better task completion and objectives, and removes subjective human elements. However, it can also be argued that robots should always remain subservient to human agency and demands. The main thing to consider is that human–robot teams are a new kind of automation that is evolving in its formation, role definition and task assignment. Additionally, as teams evolve humans might not need to retain leadership over all the aspects of the task. The paradigm of the human as the decision maker or system supervisor, as set out by Licklider (1960), may need to give way to a future in which the authority in a human–robot team is given to the most appropriate team member, independently of it being human or machine.

Manipulating the status of the human and of the machine by assigning roles to the participant and telling them that the machine is their partner, supervisor, peer or subordinate is common in the field of HCI. The use of such minimal labels has proven to be successful in previous research to create status effects (Hart and Staveland 1988; Hinds et al. 2004). When humans are told that they are working with a subordinate they rate themselves higher in their leadership role versus when they are told they are working with a supervisor; when participants are told they are working with a peer the tendency is to rate their own leadership in the middle. For the purpose of this task the robot was presented as a partner that could aid in the design task. Words like supervisor or subordinate were explicitly avoided. The leadership roles over the task were solely decided and set by the participant.

Performance shaping factors

Different architectures for human−robot teams (HRT) have been designed and identified in the literature to organise, assign roles, select and evaluate team members. A universal, performance evaluation model which can be used for HRT does not currently exist. HRT configurations can be differentiated by several factors that are constant across the literature: 1) online vs offline team planning and performance analysis; 2) human-centric vs robot-centric distribution of tasks; this determines the workload for each; 3) control authority structure defining where the critical decisions are and who will make them; 4) communication protocols (haptic, audio, visual, data, etc.) including the information that is capable of being shared by the HRT; 5) autonomy level of the robotic agent or agents which determine the amount of human intervention needed; 6) sensors and their function in defining how each agent (human and robot) would receive information from the environment.

Singer and Akin (2012) make a comprehensive review of each of these categories and their influence on the HRT performance and configuration. The HRT model used in this dissertation is human-centred. The primary evaluation criteria for the design scenario is the effect of the design decisions on human performance, and the way in which human performance has been influenced by the actions, decisions and level of automation of the system (Parasuraman et al. 2000). The design task for this exercise, in the automation and action selection scale, situates itself in the middle level of 5 (Figure 4-3).

HIGH

10. The computer decides everything, acts autonomously, ignoring the human.
9. informs the human only if it, the computer, decides to.
8. informs the human only if asked, or
7. executes automatically, then necessarily infomr the human, and
6. allows the human a restricted time to veto before automatic execution, or
5.executes that suggestion if the human approves, or
4. suggests one alternative
3. narows the selection down to a few, or
2. The computer offers a complete set of decision/action alternatives or
1. The computer offers no assistance:human must take all decisions an actions

LOW

Figure 4-3 Parasuraman et al (2000), levels of automation of decision and action selection on human interactions with automation.

Three different taxonomies have been accepted for HRT. The taxonomy presented by Gerkey and Matarić (2004) assigns task allocation relative to the robot performing the task and the team configuration but does not consider the planning portions of the design problem. Yanco and Drury (2002) proposed a taxonomy emphasising the team dynamics and physical characteristics (human to robot ratio and types of robots) as well as the interaction mechanisms between humans and robots and the degree to which robotic agents are dependent of humans. Steinfeld et al. (2006) provided a more general categorisation for all the common metrics that apply to HRI. The metrics are split into human, robot and environment categories that define the overall system. His classification specified the details of each agent and its performance on the task together with the interactions between them, although it does not provide a framework to combine the different performance metrics into an overall picture. Its main focus is to evaluate how the human and the robot perform as a team rather than to evaluate task-specific performances. These taxonomies provide a background to the design of the task and the selection and establishing of the evaluation metrics. However, due to the diverse range of human–robot applications not all the metrics from one taxonomy can satisfy the specific needs and application space of the design task. It has been necessary to rely on a combination of metrics that might not be comparable with other applications. In order to evaluate them, familiar methods of scoring (Likert-scale) have been used as a means to develop a cohesive framework. This is accepted in the HRI community due to the lack of a standard evaluation framework (Steinfeld et al. 2006).

The design of the HRT has been analysed following the three aspects proposed by Steinfeld et al. (2006): human, robot and environment. An important thing to note is that the taxonomies described above have been developed for task-oriented robots (move things from A to B, assembly of a component, etc.). The design process is an intellectual task, without expert robot users and which requires additional considerations for humans to cede and share agency during its development.

4.3.1.2 Trust

There are many definitions of trust in the literature across different domains, from human personal trust (Mayer et al. 1995) to human-automation trust (Lee et al. 2004; Madhavan and Wiegmann 2007). However, there is an agreement that trust is an essential aspect of any relationship or partnership and that team dynamics are largely based on notions of trust (Marble et al. 2004; Hancock et al. 2011a; Charalambous 2014). Furthermore, trust in the individual team members is largely identified as a crucial element of effective teamwork. It is important to emphasise the relational nature of trust and recognise that trust might not necessarily be between what is *"traditionally considered sentient organisms"* (Hancock et al. 2011b, p. 24) but it can involve other agencies, such as robots, that might not express a self-determined intention. The preferred definitions of trust relevant for this research are the one coined by Hancock et al. (2011b, pp.24) *"Trust is the reliance by an agent that actions prejudicial to their well-being will not be undertaken by influential others"* and the one from Lee et al. (2004, p.51) who define it as *"the attitude that an agent will help achieve an individual's goals in a situation characterised by uncertainty and vulnerability"*.

When the human trusts in the capabilities of the robot to achieve a particular result, he or she can let the robot perform accordingly. Without trust in the capabilities and intentions of the team partner, it is safe to assume that there will not be team dynamics (Kruijff and Janıcek 2011). Additionally, the specific capabilities in which the human feels that he can trust the robot will become the basis of the collaborative task. The human will delegate and cooperate with the robot based on the robot's capabilities that he or she perceives (Kruijff and Janıcek 2011)

Trust is a dynamic concept that evolves through interactions and is continuously calibrating throughout the task. The human teammate is adjusting and changing his or her degree of trust in the robotic system based on the outcomes of the robot's performance at each stage of the task (Figure 4-4). This continuous calibration of trust can have effects on the human reliance on the system and hence on the overall HRC during the process . Bruemmer et al. (2004) describe trust as a moving target that is continuously negotiated throughout the task.

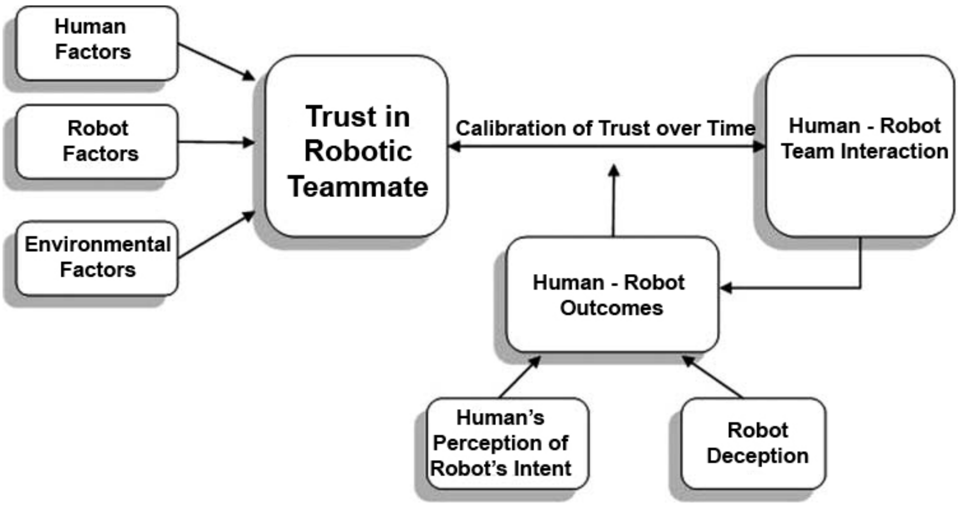

Figure 4-4 Hancock et al. (2011) A conceptual organisation of human–robot trust influences.

Trust in automation is a well-studied concept in the literature; human factors that contribute to increase or decrease trust in the system have been identified and used to explain why automation sometimes leads to overall lower team performance. However, trust in robots is a more recent concept loaded by the high expectations that humans have of robots. Little research has been directed to address trust in human–industrial robots' interactions (Park et al.

2008; Charalambous 2014). As robots become more ubiquitous researchers no longer apply the concepts of trust associated with automation to human–robot teams due to the differences between both. The robot used in this task is not a mobile nor a smart robot; however, for most participants this was their first sight and interaction with a robot. The anticipation, in some cases, was in line with behaviours expected from smarter robots.

The literature suggests different elements influence trust in HRI in relation to the human partner, robot elements and operational environment or task elements (Hancock et al. 2011a; Charalambous 2014). Each trust theme with its corresponding sub-themes (Figure 4-5) is described in the following sections.

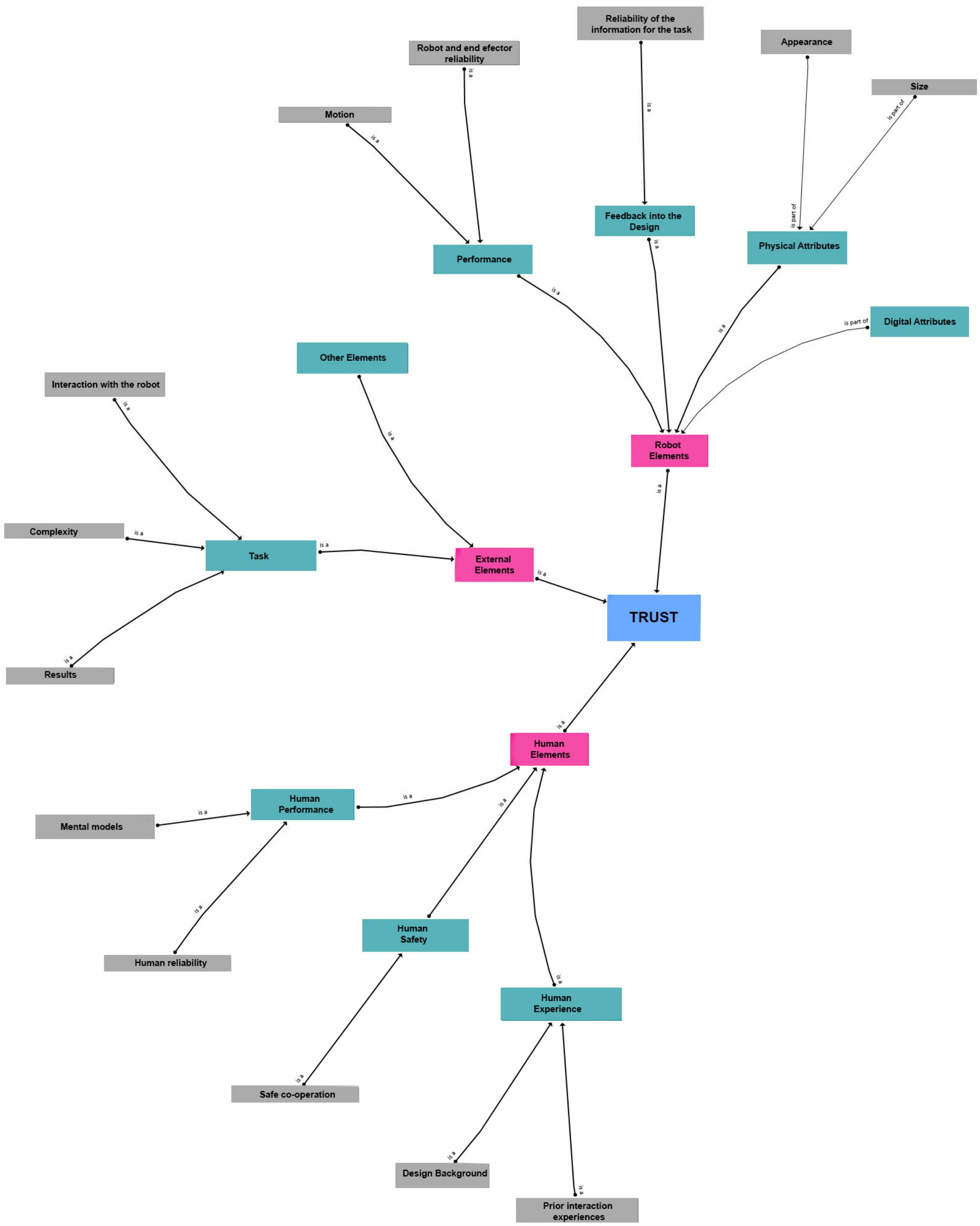

Figure 4-5 Trust themes and sub-themes.

4.3.1.2.1 Human elements

In HRI processes, the nature and characteristics of the human partner are important in enabling and defining human trust and acceptance of the robot (Park et al. 2008; Hancock et al. 2011a). Contrarily from robot elements, human elements are unstable, varied, uncertain and lack repeatability and accuracy; it is for these reasons that humans are commonly acknowledged as a source of uncertainty. Furthermore, human cognition is not directly observable. The human factors that influence behaviour and prevent consistent performance can be divided into physiological factors, cognitive factors and personality-based factors:

- Physiological factors include the type of task, fatigue, workload, skill level, environment, food or caffeine, physical comfort.
- Cognitive factors include mental workload, trust, situation awareness, mental models, emotional state, expertise, previous experiences, amount of training received and self-confidence (Pina et al. 2008; Oliff and Williams 2018).
- Personality-based factors include demographics, personality traits, attitude towards robots, comfort with robots, self-confidence and propensity to trust (Hancock et al. 2011a).

Significant research has been carried out over the last 60 years from a human factors perspective, to investigate and model the influence of these different factors on humans operating with robots. Hancock et al. (2011a) have identified, across research studies and papers, the most influential human factors influencing trust development in HRI to be human mental models, expectations, the perceived safety of the robot, and human personality traits. However, the decision to trust or not automation remains at the discretion of the human at the moment of the interaction, rendering a layer of unpredictability on how people will use automation and in which circumstances (Parasuraman and Riley 1997). Having granted this discretion, rather than including metrics of every sub-class which is inefficient, the research has focused on looking to at least one metric from each class, which has enabled better team performance evaluation in the past (Pina et al. 2008). Human evaluation metrics have been grouped under: human performance, human experience and human safety (Figure 4-6).

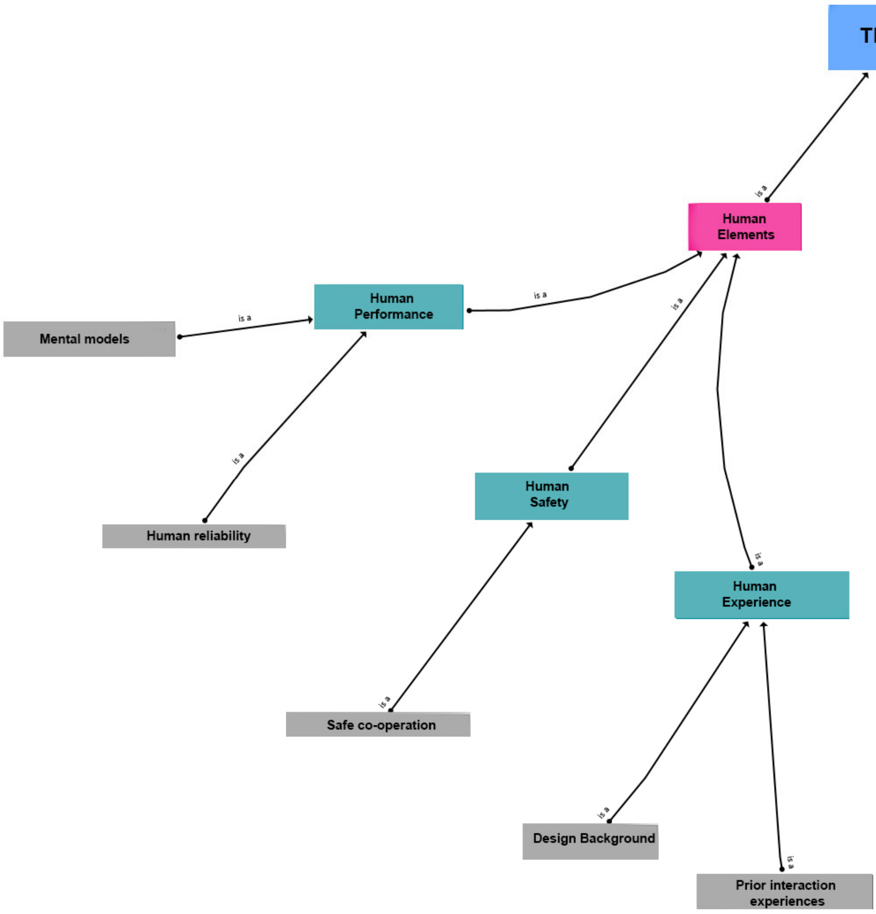

Figure 4-6 Human elements affecting trust.

Human performance

Human performance refers to the decisions made and actions taken by the humans while working with the robot. Parasuraman et al. (2000) describe human information processing as a four-stage model consisting of: 1) information acquisition, 2) information analysis, 3) decision and action selection, 4) action implementation. For the design task the stages of information acquisition and analysis are merged as the problem recognition stage. Differentiating between both in a design task is not simple as they occur closely together in the designer's mind. These three stages (problem recognition, decision and action selection, and action implementation) are measured and evaluated based on the actions taken by the designer and are considered as observable metrics of human performance.

The human role in the task is also a factor that affects how humans perform in an HRI scenario (Steinfeld et al. 2006). Scholtz (2002) identifies five roles that the human may play (supervisor, operator, mechanic, peer and bystander), each of which requires different human attitudes and awareness. The peer role, which is the one that concerns this dissertation, is described by Scholtz as one that does not suggest that human and robots are equal but describes a situation in which each contributes their skills to the team. However, the ultimate control remains with the user (Scholtz 2002b). Human performance is dependent on human mental models, and human reliability explained below (Steinfeld et al. 2006).

Human mental models

A mental model is a conceptual framework for describing, explaining and predicting experience (Rouse et al. 1992). In the field of HRC, literature has suggested that when interacting with robots, factors such as the human expectations and the human mental model of robots and their behaviour are important for harbouring trust and acceptance (Broadbent et al. 2009; Ju and Takayama 2011). Humans determine their actions and performance based on the mental models and representations that they have formed from other humans, animals or machines based on previous specific interactions with them (Phillips et al. 2011). If humans have little experience, or the object is unfamiliar, the mental model would be incomplete (Gill et al. 1998).

As models guide action, incomplete or inaccurate mental models can be problematic for the development of an effective collaboration. An accurate model, on the other hand, will serve as a vehicle that enhances collaboration and allows the human to predict avenues for future development of the partnership (Wickens and Hollands 2000). This includes an accurate and complete understanding of the robot’s true capabilities and range of actions and inactions: what is its intent, what it can do, what it cannot do and why does the robot do this? Human’s trust in robots is largely based on what the user perceives the robot’s capabilities to be, rather than on the robot’s actual capabilities (Charalambous 2014).

Human reliability

Human reliability, in the context of this dissertation, is a construct of two cognitive factors for human behaviour. It is a composite measure of self-confidence and situation awareness. Differently from mental models which refer to long-term knowledge, the two parameters that form reliability refer to dynamic knowledge and are based on the human perception of self. Humans are a crucial part of the socio-technological HIRC system; however, humans tend to overestimate their abilities (Drury et al. 2003). Human characteristics that limit human performance can be augmented by the robot if the human allows for it by being aware of his or her limits. A limited perspective or the fact that humans cannot see all there is to see and a goal-oriented mind set are, amongst others, human limiting characteristics (Energy 2009) which the robot can augment in design processes.

Situation awareness (SA) is defined *as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"* (Endsley 2006, p. 529). SA in the human–robot design team includes awareness of the robot, what it is doing at each moment, awareness of the material, end effector and all other factors in the environment that might affect the operation. It measures how much the human is mindful of his or her own capabilities (self-confidence) and the robot capabilities, and receptive to the robot, material and surroundings.

Human reliability becomes especially relevant as the robot will be responsible for particular parts of the task. The human will have to rely on the robot that it will perform its tasks correctly. If the human relies only on himself or herself and does not trust the robot, he or she will have to spend additional resources looking after the robot and will not allow the robot to perform its part to full capacity.

Human experience

Human experience refers to cognitive constructs that existed before the design exercise was executed and observed. These include design background and previous experiences. These parameters can offer an understanding of what is motivating the participant behaviours beyond what is happening during the task. It can also allow the establishment of stages during the designer training where designers are more suited to start interacting with robots, moments where their background and experiences allow them to feel comfortable to cede agency to others. The information required about the participants to define the different profiles is based on the literature and consists of age, sex, and year of study.

Human ability to understand and process information arranging it into patterns is largely related to how much is known about the architecture of such information (Lansdale and Omerod 1995). As a consequence, more experience allows for a better understanding and hence a shared dialogue and collaboration with the robotic partner that would not be possible with less experienced users.

Human safety

Human safety has recurrently emerged as a key factor in HRI and HRC research (Bartneck et al. 2009a). Additionally, trust in the robot is highly influenced by personal feelings of safety during the interaction (Charalambous et al. 2016). Human safety in this research is evaluated under the metric of safe cooperation. Safe cooperation describes the perceived safety and the level of danger that the participant feels when interacting with the robot; it also describes the participant' s level of comfort during the interaction. A positive perception of safety has been constantly shown as a key requirement for robots to be accepted as partners and co-workers in human environments (Saerbeck and Bartneck 2010). Charalambous (2014) identifies perceived safe cooperation as one of the three key design aspects that foster human trust in the industrial robot, the other two being perceived end effector reliability and perceived robot motion (Charalambous 2007).

4.3.1.2.2 Robot elements

"What matters for the human-robot relation is how the robot appears to human consciousness" (Coeckelbergh 2011, p.198).

Robot elements and performance are discussed to understand how they affect the participant's trust in the robot. Researchers have continuously speculated that the characteristics of the robot are the main contributors to human trust and that even simple robot qualities can have a strong impact on the mental model that the human forms of it (Ososky et al. 2013). On his meta-analysis of key robot factors that affect and drive trust in HRI Hancock et al. (2011a) distinguish two main groups:

- Performance-based factors including behaviour, reliability, predictability, failure rates and transparency.
- Attribute-based factors including appearance, type, size, proximity.

A better understanding of the robot's contribution to the team including its capabilities, and limitations will invariably increase the human trust in the robot (Hancock et al. 2011a).

Two additional factors specific to the design of the task and relevant to design HIRC in general are proposed and included in the questions and evaluative metrics. These are:

- Programming-based factors which relate to the digital interface with the robot.
- Feedback into the design task, referring to the robot digital contribution to the design task.

For definition and clarity robot elements have been subdivided into physical attributes and performance (Figure 4-7). However, all of them come together to make a single measure and cannot be treated in isolation. Appearance and motion or reliability and size, etc. cannot be decoupled. Different motions by the same robot would produce different feelings and a different size of robot doing the same motions would produce a different emotion in humans.

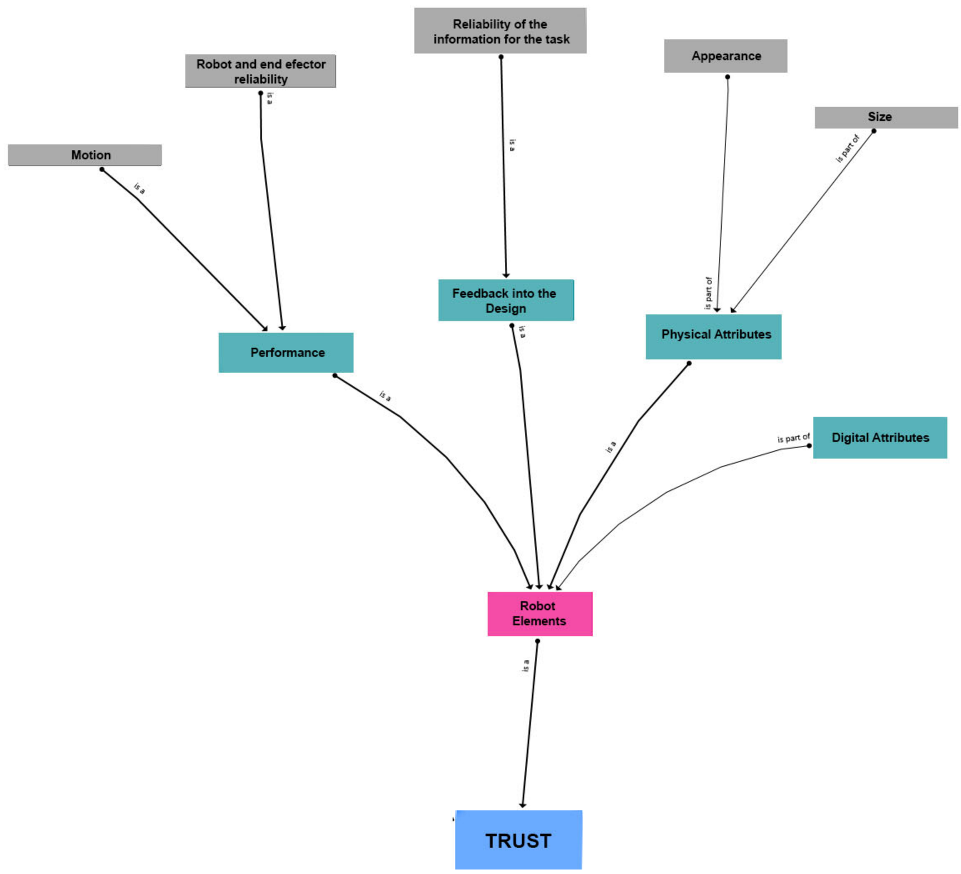

Figure 4-7 Robot elements affecting trust.

Robot digital attributes

Industrial robots are mainly preprogramed machines not conceived for collaboration. Robotic software architectures and user-interface designs are not made to accommodate a human in the loop. The limited studies in HIRC focus on the physical interaction between the human and the robot during programmed tasks (i.e. robots assisting humans in assembly tasks, human–robot turn taking for a joint plan, transferring a number of objects from one side to the other, etc.). Research in the literature of human–robot and human–industrial robot interaction does not account for direct programming of the robot by the user. Evaluation metrics for HRC and HIRC are reflective of this. The digital programming of the task as a variable, in the literature, is considered as done by someone else and measured as the trust in the 'robot programmer'. Participants are conscious that *"they are not trusting the robot but the person who set it up"* (Charalambous 2014).

Designers are not using robots for programmed, repetitive tasks. The collaboration in a design scenario is not limited to the physical aspects of the task; designers have to relate their design thinking to the robot's physical and digital capabilities. Furthermore, designers need to engage with the possibilities and constraints of the machine in an intellectual way, hence the need to add extra evaluation factors that consider the digital attributes of the machine. The complexity or opaqueness of the robot software and interface can affect their overall perception of the robot as a partner. If designers feel it is difficult to communicate their intellectual intentions to the robotic partner, they might see the robot as an obstacle rather than a collaborator, even if the physical communication is clear.

Robot physical attributes

Robots act in a different manner in the physical world to other kinds of automation and to other computers. Different robots have different embodiments and degrees of capabilities of altering their environment but all of them interact with the physical world and its actors. For HIRC to be successful humans need to feel physically and mentally safe and comfortable with robots. In order to provide physical safety robots must not injure humans. In order to provide mental safety robots must not scare, surprise or displease humans and in general should not make them feel uneasy (Inoue et al. 2005). Ososky et al. (2013) found that humans quickly form mental models of robots around superficial characteristics, including their physical form. These mental models will influence how participants relate to the robot in the future and may prove difficult to change.

Robot size

Robot size is a physical attribute that has been recognised as contributing to the human personification of and relation with the robot. The human proximity to the robot in relation to the robot size has been found to influence the level of trust that the robot generates in the human, i.e. humans trust a small robot more than a large one when they have to be in a tight space with them as in a corridor (Tsui et al. 2010). Industrial robot arms, due to their machine-like appearance, large parts and high payloads, may have a different relation between size and trust than their less machine-looking counterparts. It has been suggested that the initial feelings of fear, distrust and intimidation possibly provoked by the large size of industrial robots can be alleviated by fluid, non-erratic motions (Charalambous 2014).

Robot appearance

The robot's physical appearance can change human perceptions of its reliability. The way the robot looks leads human to assign it different personality traits from cheerful, to responsible or aggressive (i.e. a robot with spider-looking legs is found to be more aggressive than a robot with human-looking legs, indicating a general lack of understanding of how robots operate and work both mechanically and conceptually) (Kiesler and Goetz 2003; Broadbent et al. 2011; Phillips et al. 2011; Ososky et al. 2013) .

Anthropomorphising is a necessary step in the human process of rationalising the behaviours of non-human objects including computers and robots (Duffy 2003), hence the constant speculation that highly anthropomorphic robots are more likable. However, the literature provides contradicting results with some studies suggesting that robots should not be too human-like, whereas other agree that a greater human-like appearance will make them more engaging and likable (Bartneck et al. 2009a; Broadbent et al. 2009; Ososky et al. 2013; Xu et al. 2015). At the same time, the literature agrees that the appearance of the robot influences human expectations about its abilities (Phillips et al. 2011). Charalambous et al. (2016) in their metrics for human trust in industrial robots, speculate that the industrial appearance of the robot arm makes people perceive them as tools, hence the influence of its appearance in the development of trust is not as great as for robots perceived as social or health assistants.

Robot performance

Robot performance factors, and specifically its perceived reliability, have the greatest influence on human trust (Lee et al. 2004; Hancock et al. 2011b; Charalambous et al. 2016). Lee and Moray (1992) define *trust in the robot performance* as the belief that *"the robot has the hardware and software necessary to complete a task and will reliably work toward completing* *team goals".* This type of trust has also been referred to as trust in competency or ability (Lee et al. 2004) which needs to be differentiated from what Hancock et al. (2011b) define as the *trust in robot intentions*, meaning humans trust that the robot will operate towards the goals of the team in a beneficial way versus those of a deceptive robot .

Robot motion

The human tendency to anthropomorphise even simple interactions by assigning them intention becomes especially relevant when objects, including robots, are in motion. Saerbeck and Bartneck (2010) researched how participants reacted to an iRobot Roomba motions changing accelerations and curvature paths. Their reports indicate that all participants described the robot's behaviour using emotional adjectives and attributed personality to the Roomba. Furthermore, Ju and Takayama (2011) researched how people describe the motions of an automatic door. Their findings report that participants interpreted variations in the door's motion with intent describing it as reluctant, welcoming or urging. The human perception of the robot motion becomes an important factor for the development of a successful collaboration. Fluid robot motions have been constantly found as a key factor for effective human–robot teamwork that puts the human partner at ease and increases trust (Gielniak et al. 2013; Mayer et al. 2013).

Industrial robotic arms are not generally considered collaborative and this has led to the development of a number of internal and external control mechanisms such as motion range limits, robot cages, laser safeguarding zones, and locks. None of these account for the fluidity of the robot motion nor the human perception of it. These can be considered physical safety controls. As industrial robots become more available in unusual places and work closer to humans, as in the architectural design laboratory, understanding robot motion as a parameter on human mental safety becomes as important as physical safety. The implications of both are equally relevant for human collaboration.

Robot and end effector reliability

End effectors are a crucial component of the robot system. Studies in the literature point out that trust in the robot is affected by whether participants feel that the end effector is reliable to perform the task (Yagoda and Gillan 2012; Pellegrinelli et al. 2016b). In the context of design tasks, the end effectors are constantly changing; differently from manufacturing tasks. As designers iterate between materials and fabrication techniques they manufacture, hack, and create different end effectors to help them accomplish their design goals. Hence, it is important to differentiate between the reliability of the end effector and the reliability of the robot. However, literature indicates that trust in the robot is affected by how reliable participants feel the end effector to be in relation to the task. For example, in a gripping task, the pick-up speed of the gripping mechanism and its reliability has been shown to have a significant impact on participants' trust in the robot partner (Charalambous 2014).

Robot's feedback into the design task

Robot feedback is a component of the robot system. It can be seen as a separate variable from those directly related to the robot as it is enabled and designed separately. However, it is undeniable that humans can change how they see the robot system after getting and evaluating sensor data from it. Yagoda and Gillan (2012) on their HRI trust scale categorise sensor data within an 'information processing' subscale that assesses at what stage of the process a person's level of trust in the HRI system changes or varies from their initial rating. The sensor data can have the following dimensions: reliable, understandable, timely and dependable (Yagoda and Gillan 2012). The human processing and understanding of the data in its different dimensions will define their trust in the system. If the sensor information data fails in any of them, it becomes important to analyse its impact and the stage at which it failed to improve that part of the system, i.e. was it not easily understandable to the humans? Is the problem the communication interface, the format, etc? Each dimension will have its own variables, different reasons to fail or succeed and its own parameters, hence the need to categorise them as a subscale.

Feedback from an industrial robot and its effects on the HRT has not been included as a parameter in the studies found in the literature to the best of the researcher's understanding. This can be because robotic feedback is not expected in this kind of setting. Human perception of the robot information has been mainly researched in settings like rescue, military or NASA where the human agent needs to rely on the robot information while dealing with a situation; in these cases, the human would not have direct access to the information that the robot is contributing to the task. There are recorded cases in the military in which robots have not been deployed, with humans choosing to expose themselves to danger to obtain information rather than trust feedback provided by robots i.e. the SWORD, special weapons observation reconnaissance detection (Ogreten et al. 2010). In the design scenario the feedback is intended to augment the designer's understanding of the material world on the exploration of the design space rather than intended for critical decision-making and problem-solving.

Reliability & usability of the information provided by the robot on the design task
The reliability of the system has been previously described as a key aspect for human trust in the automated system. The information provided by the robot can be considered part of the robotic system. However, in the design scenario, a differentiation between the reliability of the robot's actions and the reliability and usability of the information has been made to understand at which moments in the design process designers cede intellectual agency to the machine. The reliability on the machine can be seen as trust that the robot will correctly perform the actions it is supposed to do in a physical way; designers in this case are ceding physical agency to the robot. The reliability and usability of the information implies designers trusting the robot's suggestions over their intuition or own visual feedback, shifting intellectual agency to the robot to different degrees.

Designers tend to trust automated systems as can be seen in the ubiquity and acceptance of generative design methods and their expression through rapid prototyping for the generation of early design phase models that respond to different sets of constraints (Sass and Oxman 2006). However, most of them are digitally based methods. There is a need to study the designers' acceptance of and relation to feedback from a physical device which can offer a different and sometimes contradictory perspective over the physical world to that of the designers.

4.3.1.2.3 External elements

The third main broad category of factors that influence trust in HRC can be described as environmental or external factors. These include task-based factors such as task complexity, task type, and physical environment (Hancock et al. 2011a) (Figure 4-8). The literature agrees that human error in a human−robot collaborative task is not merely a function of the human, but of how well the design of the task and the system facilitates human understanding (Marble et al. 2004). Parasuraman and Riley (1997) in their research of human factors affecting interaction with automation have found that the complexity of the task moderates the development of human trust in the system.

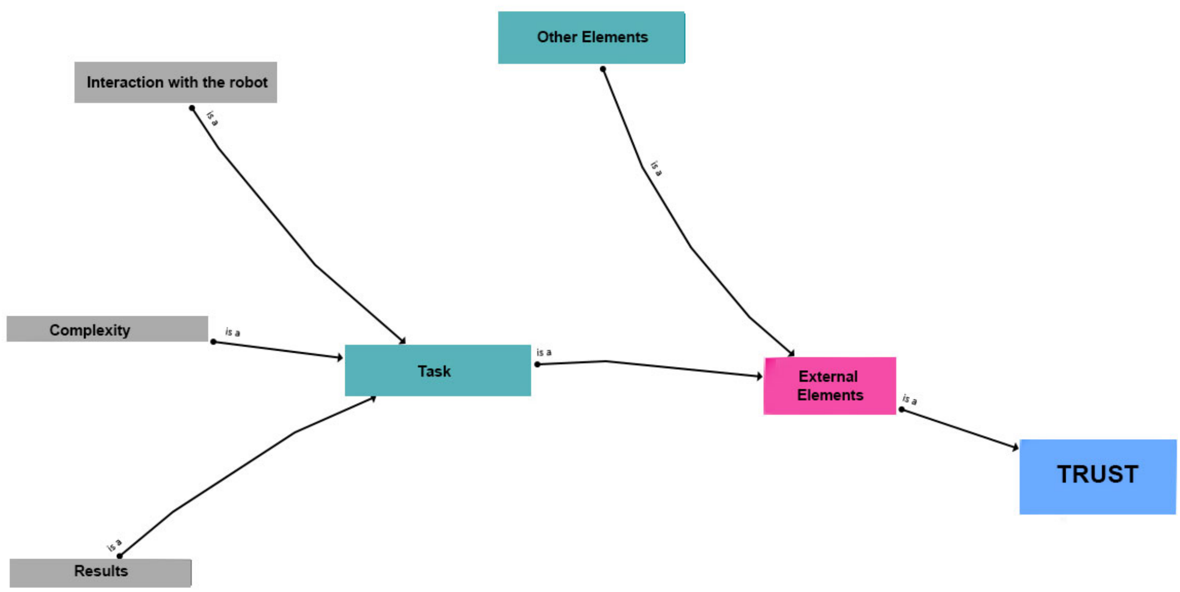

Figure 4-8 External elements affecting trust.

Task

The demands and nature of the human−robot task being performed has continuously emerged in the literature as the main source for variability of the human performance. This relation led NASA to develop a task load index framework to identify a number of task structures, with different combinations of physical and mental cognitive loading, to assess and analyse the different task factors and their relative impact on human performance (Hart and Staveland 1988; Hancock et al. 1995). A multi-dimensional task rating scale was proposed with different task demand characteristics and the factors they influence. Task duration, frustration with the task, and task results have been included amongst the factors that influence human workload and ultimately performance (Hart and Staveland 1988; Hancock et al. 1995).

Task interaction with the robot

Teams are able to complete complex, stressful and ill-defined tasks based on each member coping with their individual level of work and the team level task work (Salas et al. 2008). On a human−robot scenario the understanding of the robot′s actions and intentions by the human partner may become more important than robot reliability or performance (Bruemmer et al. 2004). Studies in psychology show that effective team collaboration requires participants to plan and execute their actions in relation to what they anticipate from the other team members. A reactive situation when team members only react to each other's current activities creates higher levels of stress and workload making for ineffective team work.

Clear definition of the tasks for the robot to perform as well as for the human; is crucial to reduce the mental workload and distrust of the human in the robot partner and to generate clear expectations from the collaboration. Designers are not expert robot users, hence their knowledge about how to complete the HIRC design task at the beginning of it may be limited. During the task, the designer's understanding of the robot and of his or her role in the task grows, but he or she will need to rely on the robot teammate and its actions for a successful task interaction to happen (Harriott et al. 2015). Research indicates that people prefer to use an ineffective system that they understand over a high-performance system that is confusing (Bruemmer et al. 2004).

Task complexity

Task complexity is an important factor in the level of trust and reliance that the human operator puts on the robot (Charalambous et al. 2016). A high degree of complexity can result in high workloads for the human partner. High levels of workload and stress can lead to under or over-reliance on the robotic system. A task load suited to the cognitive needs of the participant will prevent work overload and influence trust (A. Cosenzo et al. 2006). Non-challenging tasks are generally more conducive to human trust in the robot partner (Charalambous et al. 2016).

Task results

Task results are related to the successful outcome and completion of the task by the HRT. The literature consistently indicates that human trust in the robot system is largely based on whether it is able to successfully complete its tasks (Hancock et al. 2011a; Charalambous 2014). Additionally, the outcome of the human−robot task will calibrate the human trust in the robot over time. For an exploratory design scenario, successful completion of the task is largely based on the human perception of it rather than quantitative measures.

4.3.1.3 Collegiality

Collegiality is defined as the relationship between colleagues united in a common purpose where both respect each other's abilities to work towards that purpose (Merriam-Webster 1828). It can also be defined as the cooperative interaction amongst colleagues. The abilities of the colleagues do not necessarily need to be the same but they need to be complementary to achieve the common goal. For the purpose of this research, collegiality evaluates the robot's perceived character traits related to those of a team member which could qualify it as similar to a human partner. Collegiality consists of the three following indicators (Figure 4-9).

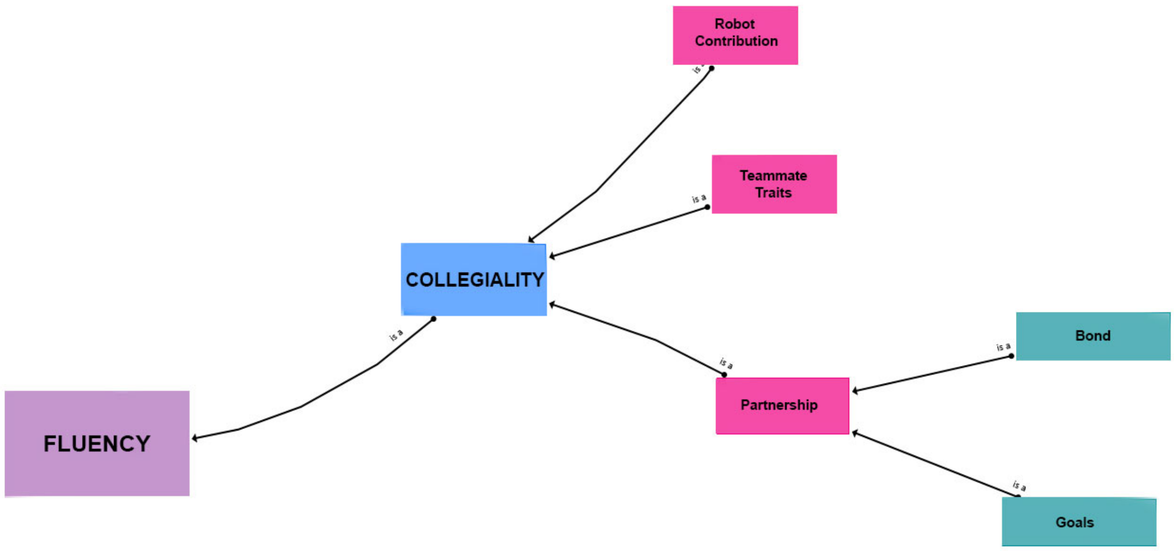

Figure 4-9 Collegiality sub-themes.

Robot contribution

This is a measure to evaluate the robot's contribution to the team as perceived by the human partner. The contribution of the robot is a relative measure as the robot is not learning nor adapting in this task. The contribution of the robot includes considerations outside the defined task and are related to its contributions to the design activity.

Teammate traits

This measure evaluates the perceived character traits of the robot related to it being a team member (Hoffman 2013b) i.e. the robot as intelligent, trustworthy, and committed to the task. Bratman (1992), in his detailed analysis of a shared cooperative activity defines certain prerequisites for an activity to be considered shared and cooperative. These include mutual responsiveness, commitment to the joint activity and commitment to mutual support. Furthermore, Cohen and Levesque (1991) provide a framework to build artificial collaborative agents. They see the commitment to the joint activity not only as a commitment towards a shared goal but the commitment from all team members to mutual communication about the state of the goal. Teammates are committed to inform the team when they reach the conclusion that a goal is achievable, impossible, or irrelevant (Hoffman 2007). Some of these principles have been used in research on human–robot teams (Alami et al. 2006; Hoffman and Breazeal 2010).

Teammate traits include a measure for gender. The literature suggests that gender is an important quality in HRI, especially in relation to teammate traits. People who give the robot a female name see it more as a subordinate, whereas those that give it a male name see it as a partner (Hinds et al. 2004). In the context of assistance robots, Dr Nóra Ni Loideain describes how the robot Amazon Alexa, which is decisively gendered female, can be described as an 'unbodied assemblage' of a normative female always ready to hear the command of her user, and with no recourse to refuse or say no. The relationship between the sex of the robot and the expected relation it will form with a human becomes decisive.

Partnership of the working alliance

Partnership is measured by adapting an existing instrument, the Working Alliance Index (WAI) (Horvath and Greenberg 1989) which is a standard instrument in measuring the quality of a working alliance between humans. Hoffman and Breazeal (2010) proposed an adaptation of the working alliance index to a human–robot teamwork scenario. This measure is made up of two sub-scales, the 'bond' subscale and the 'goal' subscale in addition to one individual question. For this research the two metrics of the working alliance partnership are defined as follows:

Goals: When the participant felt that the robot understood what he or she was trying to achieve and felt that both were working together towards said goal.

Bond: For cases where a personal attachment, including mutual trust and a link of acceptance and confidence, was formed between the robotic manipulator and the participants.

4.3.1.4 Improvement

Improvement is important in a true collaborative scenario. Collaboration requires partners to iteratively adjust and learn from each other over time. Learning can be considered one way to adapt (Terveen 1995) and as team members learn and adapt the team is expected to improve. Learning can be direct (when the partner tells or shows new ways of doing things to the other partner) or indirect (when actions such as justification and explanation are required from one partner to other). As the robot does not learn nor adapt in this task, improvement only takes place in the human. Improvement is evaluated in terms of whether the participant felt that their relationship with the robot partner became better as the task progressed. This variable is important to evaluate the human perception of the team and if humans attribute improvement to themselves or to the robot – regardless of it improving or not.

Human improvement

Collaboration can be divided into short term and long term. Short-term collaboration is the one that happens within a single session, while long-term collaboration happens across multiple sessions (Terveen 1995). As participants become more familiar with the robot they would learn and adapt to its needs. Human improvement is an individual measure that has been used in the literature to understand the human perception of the team performance over time.

Robot improvement

Robot improvement is considered as the contribution of the robot to the improvement of the team. Although the robot is not learning nor adapting it is presented, for this exercise, as a team member with very defined tasks. Moreover, it is a team member that can provide advice to the human partner even when it lacks any autonomy to take decisions. For this scenario the improvement of the team has to be considered solely on behalf of the human. However, measuring the robot improvement, as perceived by the human, is used as means to explore potential downstream outcomes of collaborative fluency. These results may include the robot's perceived intelligence but most importantly the human confidence in the robot and its commitment and contribution to the task (Hoffman 2013b).

4.3.1.5 Robustness

Robustness is defined as the opposite of dysfunction. The features evaluated under this category are considered fundamental for the functioning of a team. Divisional task teams have been shown to have a higher level of robustness and perform better on tasks with a higher level of uncertainty (Macmillan et al. 2004), whereas functional teams perform better in predictable tasks. Robustness in teams is related to the task and to the division of labour for team members in the task. To evaluate the robustness of the design HIRC five main parameters were identified: reliance, shared identity, responsibility, attribution of credit and attribution of blame (Figure 4-10).

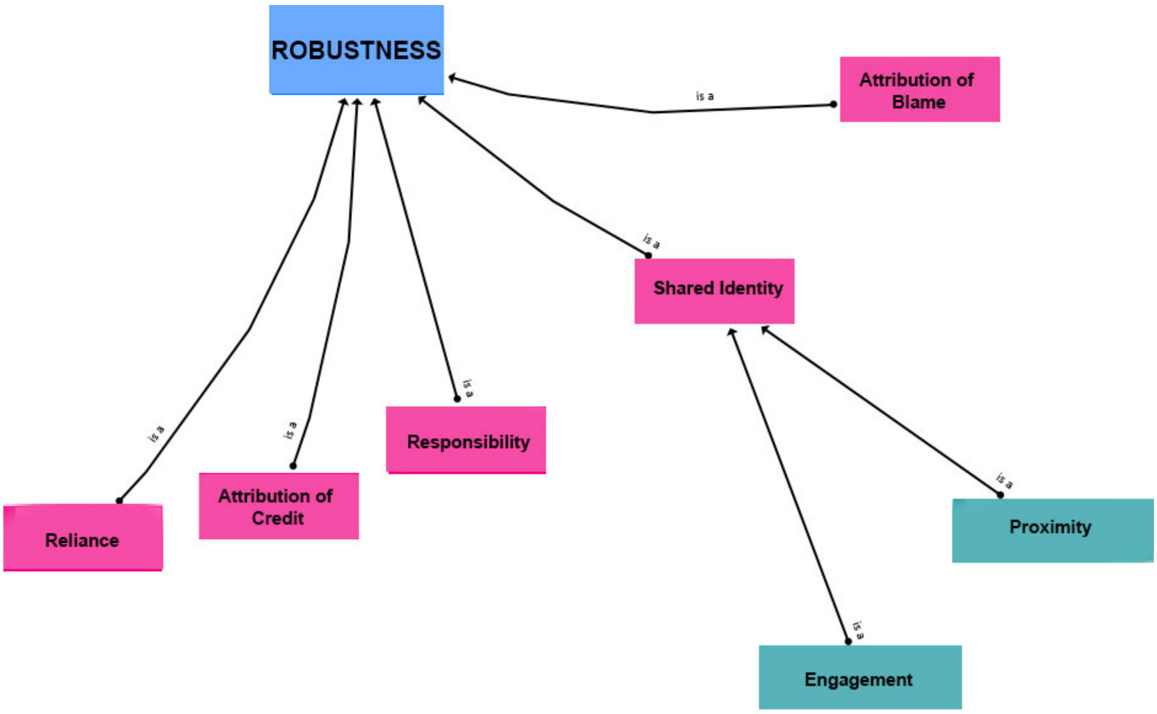

Figure 4-10 Robustness constructs.

Reliance

Reliance is normally defined as the dependence on or trust in someone or something (OED Online 2017). Trust is described in the literature as a main contributing factor to reliance on automation (Lee and Moray 1992). For the purposes of HRC reliance can be described as the relationship between the human levels of trust in automation and self-confidence in his or her own abilities (Marquez et al. 2017). The extent of this reliance is less obvious when people are asked to use a new technology, but it is also crucial to the success of the new technology or tool. Getting people to rely on robots has been a crucial concern for roboticists and researchers in the field of HCI and HRI (Hinds et al. 2004).

Reliance is a situational parameter. Other factors at the moment of the interaction may come into play to inform the designer's decision to rely or not rely on the robot. Factors that have shown to affect reliance, are previous experiences with automation or with a particular automated system, interest in the task, fatigue, external policies regarding the use of automation, and responsibility. It is useful to keep these potential influences on reliance in mind when evaluating the results from the case study to understand what caused designers to take certain actions and adjust their approach during the development of the task.

An excessive degree of reliance can have catastrophic consequences and result in a lack of human input on the design evolution. An overly reliant person will be placing too much trust in the robotic manipulator, thereby reducing his participation in monitoring its performance in the case of an industrial setting (Parasuraman and Riley 1997) and in monitoring the design output on a design setting. Endsley (2006) describes this as a loss of situation awareness. Parasuraman et al. (1993) describe this as complacency. The reliance on the robot as a partner is closely related to the sense of responsibility for the task.

Reliance is continuously changing during the HRI process and is closely related to the system reliability. Changes in reliance result in changing the autonomy and trust that the person gives to the robot system. Studies have shown that when a drop in the system reliability occurs users immediately switch away from the automated system, whereas an increase in reliability does not make them return to the system as fast. Consequently, the degree to which the automated system is reliable has an important impact on humans' reliance. However, despite humans ignoring automation they will not ignore it more than they would another human. Research investigating people's reliance on automated assistance versus assistance by other humans (Madhavan and Wiegmann 2007) and machine-like agents versus human-like agents (Parasuraman et al. 2014) has shown that even in the cases where the same information is provided by both, people tend to rely more on the automated system than on the human partner (Dzindolet et al. 2003).

Risk is another factor that influences reliance, as the levels of risk escalate humans rely more on automation rather than humans as support aids. Humans are extremely sensitive to automation errors when compared to human errors, leading to under reliance on the automated partner. At the same time, they are more likely to trust automation advice when compared to human advice, leading to over-reliance on the robot partner.

Shared identity

Shared identity can be defined as those moments when the participant felt closer to the robot and perceived a common ground between him or her and the robot. The literature has found that an emphasis on similarities, specially 'shared goals', can induce the sense that a person is part of a team and become a factor that leads to the development of a shared identity (Groom and Nass 2007). People respond differently to technology when they perceive similarity and a shared identity. In a team configuration, achieving a shared goal is easier than achieving individual goals. Perceived shared identity aids decision-making, communication and collaborative action. Additionally, it facilitates collaboration as the person is more likely to be confident in the robot's capabilities and his or her own abilities to interact effectively with it. Research in the literature has not found any notable differences in shared identity in human–robot teams with human-like robots compared with machine-like robots (Hinds et al. 2004).

Responsibility

As robots increasingly support humans in accomplishing their tasks, questions arise regarding who is responsible for the task. Also, who should be blamed if something goes wrong. Studies in autonomous and health robots have started to look into these questions and research results have shown that when an unexpected situation occurs people get easily confused and are not sure who to blame: the robot, themselves or other humans (Kim and Hinds 2006). Additionally, they would attribute incorrect blame or too much responsibility to the robot.

For the task in the research the robot was presented to the participants as a partner that collaborated in their design process. Hierarchy is an important factor in human willingness to assume responsibility versus allowing others to assume it (Hinds et al. 2004). Humans' perception of the hierarchy of others' status is crucial in how we determine their capabilities and performance. How the robot is presented clearly affects the willingness and attitudes of people towards it (Strodtbeck et al. 1957). Researchers have found that even arbitrarily assigned labels (i.e. leader, expert, etc.) have influence on the competence and attributes that people assign to those of higher status and hence their sense of responsibility and behaviour in respect to them (Strodtbeck et al. 1957). People are more willing to share responsibility with robots that are in a position of authority (Hinds et al. 2004).

Reliance and responsibility are usually related and people who rely more on the robot are more likely to cede it more responsibility. This results in an inverse relation in which people who rely more on the robot feel less responsible for the task. Hinds et al. (2004) in their research comparing reliance and responsibility in teams with machine-like robots and human-like robots have found that people cede more responsibility to human-like robots. This has led them to suggest that machine-like robots might be more appropriate for situations which demand a need for personal responsibility. However, this can become problematic for collaborations in which the robot needs to make key decisions about the task (Kiesler and Hinds 2004). In situations where the robot cannot learn nor adapt, like the current scenario, an enhanced sense of human responsibility can prove useful as participants would be less likely to trust the robot to do tasks that it might not be equipped to perform, or that due to a change in the task conditions it has become ill equipped to undertake. In situations where humans have a high sense of responsibility, they may see the robot as a subordinate, and a tool to help them perform a task with specific functions, like a hammer or a pen, both of which have clearly defined mechanical abilities but no will and cannot assume responsibility. Researchers have been working to find the right mix between reliance and responsibility, *"in which the human relies on the robot for maximum input but does not abdicate responsibility"* (Hinds et al. 2004, p.156).

Attribution of credit

Attribution of credit and attribution of blame are associated with responsibility, indicating that in cases where participants take more responsibility for the task, they are less likely to attribute blame and credit to others (Hinds et al. 2004). Issues of credit and blame have been central to the human conception of robots (i.e. people assuming computers have responsibility for ethical issues) and are critical for effective collaboration and decision-making. The way in which robot behaviours influence where the credit and blame are placed and which robot actions trigger larger attributions of credit or blame is a rich field of study

Attribution of blame

Attribution of blame is an important indicator that measures the extent to which participants assign blame to their partners. Blame is not equivalent to the abdication of responsibility. However, people who feel more responsible for the task are less likely to blame their partner for the errors (Goodnow 1996).

Humans will be more likely to attribute responsibility to the robot for the things that go wrong than for the things that go well. If the action is repeated, over time, humans will criticise the robot for acting unpredictably, regardless of the action or the expected behaviour (Kim and Hinds 2006). Negative outbursts will only increase as the robot is unable to renegotiate the human relationship as robots are not able to change nor adapt according to human requests. Additionally, the greater the human teammate's personal investment in the teams' ultimate goal, the lower the threshold for violations of expectations (Groom and Nass 2007). As the human trust in the robot is conditional, if the robot fails to complete a routine task or acts in an unexpected way for the human it initiates a downward spiral in trust and an upward spiral in attribution of blame over the task.

Kim and Hinds (2006) report that the existence of a robot tends to enable a guilt-free direction of blame with humans blaming the robot even in cases where the fault was clearly their own. Friedman and Millett (1995), describe how people, even computer literates, tend to attribute, at times, social attributes and engage in social interaction with computer technology. Furthermore, his studies found that people's justifications for not blaming the computer refer to qualities of it that diminish its agency and thus undermine computers as the sort of thing that cannot be blamed. Attribution of blame is measured then in relation to responsibility but also in relation to the agency that designers give to the robot. Less blame becomes an indicator of less agency and can be related to the robot being seen as any other mechanical tool versus a partner.

A measure taken to minimise erroneous attribution of blame in the research task was to offer all the participants, previous to the design exercise, a detailed explanation of the sequence of actions that they would undertake and that the robot would undertake. Research in the field of attribution theory (Jones and Nisbett 1972; Ross 1977) has shown that when people have more information, they perceive actions as more transparent and are less likely to erroneously attribute blame to the others. Hence, explaining the robot's actions could lead participants to feel that they understand the robot and be more accurate in attributing blame for the errors (Kim and Hinds 2006).

Attribution of blame would most likely be informed by robotic actions as much as by the human mental models of the robot and expectations in respect of its capabilities, irrespectively of their accuracy. Participants' design background and digital understanding are also likely to contribute to their understanding of the robot behaviours and consequent attributions of credit and blame.

4.4 Summary

The implementation of technology cannot be seen as an isolated and purely technical problem. The literature suggests a range of human factors that affect how technology is perceived and how it will be adopted. In order for robots to become design partners within a holistic design environment and outside specialised laboratories the human factor has to be considered. The literature has shown, in other industries, that failure to attend to the human factors is detrimental for the adoption of new technologies. Merely fitting architectural schools and practices with robots will not ensure acceptance nor effective use of the technology by the broader architectural design community.

The concept of HRC with industrial robots is in its infancy in the manufacturing and traditional industries that work with robots. Real world applications of this concept are still limited. Industrial HRC (HIRC) in novel robotic domains such as architectural design is nascent. Additionally, design tasks require a different approach and set of metrics that are not based on efficiency to complete a task but on opportunities of discovery. At this stage it is crucial to understand how humans relate to robots and which factors need to be considered to enable the successful adoption of robots as part of the design workflow and subsequently as collaborators in the genesis of design. The theoretical framework of team fluency, collected from the literature and developed in this chapter, provides a list of the key human factors which appear to be most important for the successful implementation of HIRC. It is important to investigate each of the factors that constitute team fluency as described in this chapter.

As shown by the review, the concept of trust receives more attention as it is the foundation on which teams build and it constitutes the basis for all the other factors. Trust is a fundamental aspect of successful human collaborations and understanding how it develops when the collaborator is an industrial robotic arm is central to build the other factors that constitute team fluency hence, trust receives more attention in the number of questions asked of research participants, and its evaluation from data derived from questionnaires and interviews. The work undertaken to evaluate the proposed framework is described in part two of this dissertation.

Chapter 5 INITIAL EXPLORATION

5.1 Introduction

This chapter presents the initial explorations of an HIRC design case study of novice robot users within a real architectural design scenario. It seeks to investigate how the relationships between designers and robots start to form and whether, from the early stages, there are enablers or barriers to the design process. The exploratory case study is the first step towards investigating the role of the robot as a collaborator that augments the designer and as an active agent throughout the design process. The robot in this context gives the designer explicit rules and constraints, forcing him or her to share the design intentions in a systematic way. A working model was implemented and tested involving three sessions with each participant to introduce them to the robot, to the design process and finally to perform a collaborative design task.

An exploratory study is the first phase of a research. The general goal of an exploratory study is to provide information to contribute to the success of the research project as a whole by allowing useful amendments to the instruments used for data collection (Calitz 2009). Conducting a pilot study has the following value (Calitz 2009):

- It can give advance warning about where the main research project may fail;
- It indicates where research protocols might not be followed;
- It can identify practical problems associated with the research procedure; and
- It indicates where proposed methods or instruments are inappropriate or too complicated.

Conducting an exploratory study prior to the main study can enhance the likelihood of success and potentially helps identify potential problems with the research design, interview questions and data collection strategy that could result in a doomed main study (Thabane et al. 2010). They allow the pre-testing or 'trying out' of particular research design instruments (Van Teijlingen and Hundley 2002) and design a clear road map for the research to follow.

5.2 Description of the Exploratory Case Study

The exploratory case study selected for this work includes 31 participants who worked with a Yaskawa H5L six-axis industrial robot, foam blocks and a fixed hot-wire cutter during ten days. The exercise was set up at the Belas Artes Institute in Sao Paulo, Brazil. Participants ranged from first year architecture students to graduates with over five years of experience. None of the participants had any previous robotic experience. Participants were introduced to a robotic-design workflow, following a three-session structure as planned for the main case study. Every participant, separately, had an introduction to familiarise with the robot (Figure 5-1). Then, participants recorded a robotic program by manually teaching the robot different points before sending any code to it (Figure 5-2), with the aim of understanding its capabilities.

Figure 5-1 (Left and right) Introduction session to the robot.

Figure 5-2 (Left and right) Participant recording a program with the robot.

Finally, participants tried to fabricate their designs with the robot iteratively refining them for a negotiated result between their intent and the robot's characteristics (Figure 5-3). The researcher worked with them throughout the process, demonstrating the machine, providing advice, taking notes about the relationships that they started to form between them as a group and with the machine and carrying out semi-structured interviews.

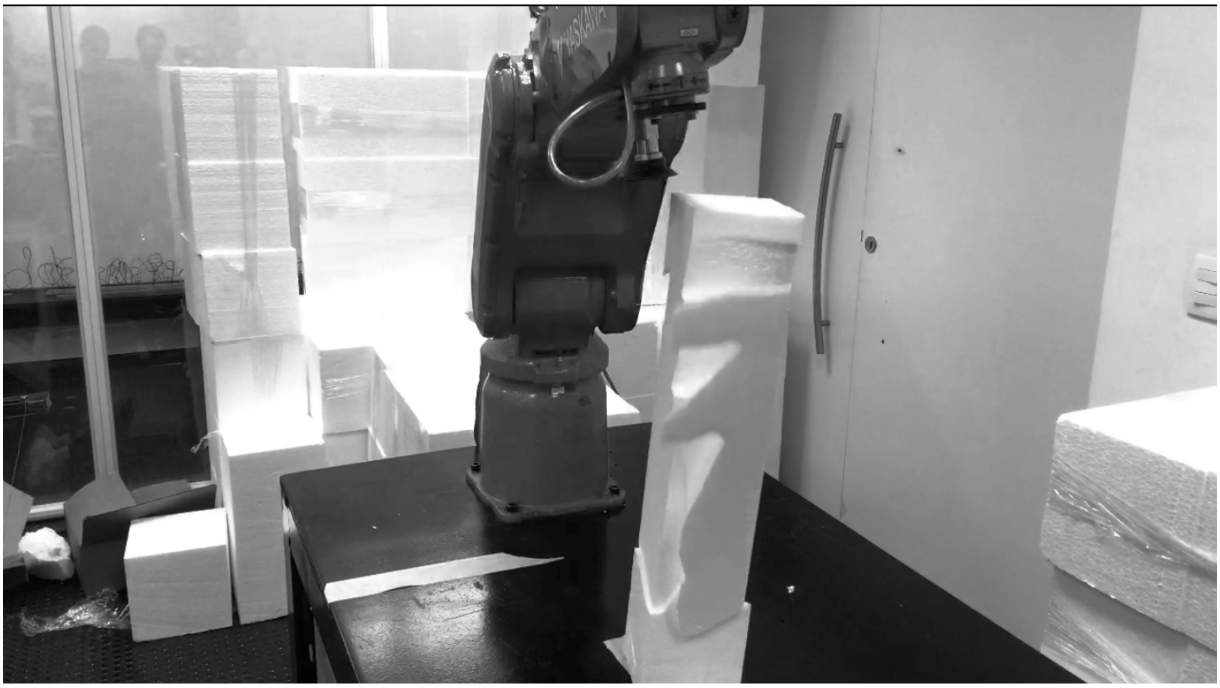

Figure 5-3 Participant material results testing the collaborative workflow.

5.3 Aims and Objectives

The aim was to uncover some of the ways in which humans negotiate a design solution with the robot and the subtle ways in which agency is shared between human and machine. Principal objectives were:

1) understanding how untrained humans relate to the robot in a design task;

2) observing their design thinking;

3) analysing how it changes and adapts to the characteristics of the robotic manipulator if at all;

4) collecting qualitative data from architectural designers as they introduce a robot arm into their design thinking and design process; and,

5) identifying key positive contributions from the robotic partner and barriers preventing the formation of relationships.

5.4 Participants

From the 31 participants, nine voluntarily agreed to take part in the interviews and for their actions and research process to be recorded. These participants were followed by the researcher during the design task. However, all of the 31 completed the design task and took part in all the sessions and robot exercises and the researcher worked continuously through the design task with all of them.

The nine participants who accepted being part of the research were four females and five males. They were a mix of architecture students from the third year (1), fourth year (2) and graduate architects with over five years of experience (6). Their ages ranged between 23 and 32 years with a $M = 28$ and $SD = 4.35$

Four participants reported not having any experience with any kind of digital fabrication machine while five reported having some experience with laser cutters and three-dimensional (3D) printers. None of the participants had any experience with robots. Seven participants reported having some knowledge of digital design tools and having used them before, with SketchUp and AutoCad being the most popular ones, while two reported not being familiar at all with digital design software. These participants were considered an appropriate match to the target group of this research: architectural designers who are novice robot users.

5.5 Workflow Methodology and Tools

All participants took part in three specific training sessions, the first one for the software workflow (Figure 5-4), a second session as an introduction to the robot and a third session to fabricate their design piece.

Figure 5-4 (Left and right) Digital workflow sessions.

Participants worked with the researcher during ten days from 9 am to 9 pm giving a good amount of opportunities for interaction, testing ideas with the robot and iterating until a satisfactory solution was found. Sessions 1 and 2 were fixed and organised as such, whereas session 3 expanded during the full duration of the design exercise (approximately six days). Participants throughout the sessions and during the ten days could interact with a six-axis Yaskawa MH5L industrial robotic arm, either to complete the task or to test ideas from their solution space (Figures 5-6 to 5-7).

The robot was placed on top of a purpose-made table, without any physical barriers between the machine and the participants. A fixed hot-wire cutter was placed to the right side of the robot. The robot was equipped with a vacuum gripper end effector that it would use to pick up the foam blocks and pass them through the fixed hot-wire to cut the material (foam). Participants had the option to digitally generate their geometries and of manually jogging the robot to iteratively test their ideas and the robot workings.

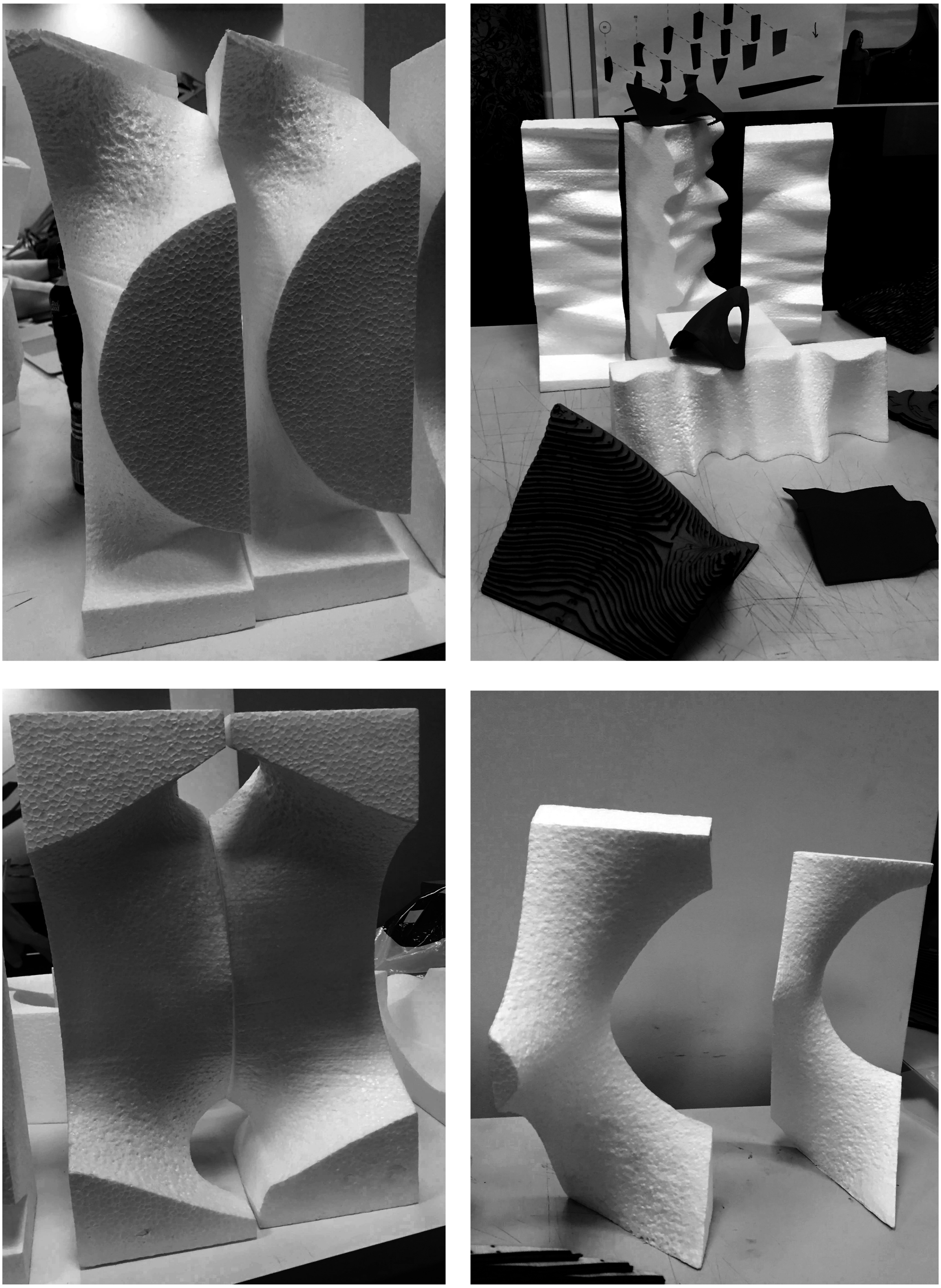

Figure 5-5 Participant HIRC results.

Figure 5-6 Participant HIRC results.

Participants were introduced to a form-finding workflow for hyperbolic structures using Rhinoceros software (Rhino) and its Grasshopper plugging. A prototypical software platform developed in C++ was used to simulate and abstract the robot's behaviour and generate the G-code required by the robot. In this same platform, robot reachability and joint angles were analysed based on the form-found geometries. The robot inverse kinematic (IK) solver was also generated to work inside Grasshopper utilising C# (Reeves 2015). Participants could keep their complete design workflow inside Rhino and export their cutting paths to the robot.

5.6 Data Collection Methods

Upon completion of the design task participants took part in a 15-question semi-structured interview led by the researcher which was recorded. A semi-structured interview approach was selected for its conversational approach and because while the interviewer has to prepare a list of questions in advance, it allows the researcher to react to the respondent and to explore the issues that they feel are important as the conversation evolves (Longhurst 2003), allowing the refinement of the questionnaire.

The lack of previous research in HIRC in design tasks, or of existing guiding frameworks, suggest an exploratory qualitative approach as appropriate for this study. A qualitative approach is considered more useful to understand phenomena within their context while revealing the links amongst concepts and behaviours (Miles et al. 1994; Crabtree and Miller 1999). The list of key human factors identified in chapter 4 is used as a guiding framework to develop a semi-structured interview in order to gain insights into the designers' thinking when including a robot arm as part of their design process. Open-ended questions were used to aid in gathering in-depth information from the participants such as: "What do you think an industrial robotic arm can bring to your design process?" Exploratory follow-up words and questions were used to extract further information from each participant, such as "How can it be useful?" The interview was designed to last 20–30 minutes and participants were interviewed individually. The interview schedule is available in Appendix M.

5.7 Data Analysis

To code the data, template analysis was used, following the guidelines established by King (1998) and described in section 1.5 of this dissertation. Template analysis allows the researcher to identify the major themes that concern the participants, emergent themes that might not have initially been considered and the relationships between them. This method allows the identification of the relevance of the factors highlighted in the literature as well as reveals specific factors that have not yet been acknowledged, and which may be specific to HIRC in the design process. Data analysis from the exploratory case study revealed a number of insights relevant to the implementation of successful HIRC in design tasks. The next sections discuss the results and their implications.

5.7.1 Positive Contributions

The participants could be considered digital enthusiasts, interested in learning and using the robot. They described their initial reactions to the robot arm as going from total awe, and curiosity, to expanding their imagination and making them wonder about the different potentials it could have. Most of them initially described the robot as an impressive, fascinating but challenging machine. A number of the robot's characteristics were identified by the participants as enablers and positive on a collaborative design process.

Rigorous exploration. Repeatability and rigour in the exploration are brought up by many participants as positive qualities a robotic partner can bring to their design process. They describe how, when they manually do form-finding exercises, they have less control, and they cannot quantify changes at each step. In a physical form-finding process mediated by the robot they can follow the exact same steps before introducing changes and evaluate different results. *"By using the robot, I could understand the material better"* CS1-002. The robot introduces novel, non-human ways (i.e. precise, measurable, rigorous) of exploring the physical material. Participants describe the robot as allowing them to reach with precision their design intent, have more control over it and giving them an understanding of the process for further experiments.

"The robot changes the way you think, and hence your relationship with the materials shift" CS1-005.

"I think it opens a range of possibilities; it gives you a way to do some forms that manually you couldn't or would be much more difficult, and gives more precision. It gives you a kind of freedom to create, even with its limitations"
CS1-008.

"It provided me a mean to reach with perfect precision the design intent. I had some limitations and sometimes it didn't come out as expected, but there were a lot of possibilities,

and I enjoyed the result very much"
CS1-003.

Engaging with the physical constraints early on. Participants feel that 3D software allows them to freely design forms which exist without physical constraints (i.e. gravity). By having to use the robot during their design they have to engage with its constraints and those from the material earlier in the design. By ceding agency, engaging and accepting these constraints (i.e. motion range, limits, etc.) they can achieve unexpected, interesting results that would not be possible without the robot partner.

"I had to change the design. First, I came up with some very complicated geometry. I tried to simplify things and later realised it turned out even better. Once I adapted my design to fit the robot's conditions, I realised I had a lot of options to build different things"
CS1-004.

"The robot provided means to simulate my design and explore different solutions while changing parameters."
CS1-009.

Ceding agency. Giving agency to the robot (incorporating its constraints) was generally taken as an advantage forcing changes in the design but making it more feasible, scalable, and rendering better, unexpected results. Participants perceive that the robot gives them freedom to explore alternatives by forcing them to design a system it can execute. However, participants acknowledge that designers are not used to working in an open-ended way where the result is negotiated between different forces (designer, robot, material). Designers are used to being in control and having the final say over their geometry.

"Either you change your design or the robot will, so it must be adapted"
CS1-001.

"We always try to dictate the rules (like in life!) But we are not always in control. It means, if we know to be flexible to the constraints, we can achieve more interesting results"
CS1-008.

"It would have been helpful if I tried to not have so much control over my design to know better the qualities and limitations of the robot. I achieved more interesting designs when I decided to reduce the manipulations over the design"
CS1-006.

"Once I adapted my design to fit the robot's conditions, I realised I had a lot of options to build different things"
CS1-007.

Participants appreciate the cases in which testing some motions that seem very simple and easy to specify to the robot (i.e. spinning) yielded impressive results which were unexpected and would not be possible for the designer to think of from the beginning or to execute without considering the characteristics of the robot.

"It opens a range of possibilities; it gives you a way to do some forms that manually you couldn't or would be much more difficult, and gives more precision. It gives you a kind of freedom to create, even with its limitations"
CS1-009.

"Even though with the machines you don't actually get to feel the materials in your hands, like the flexibility, toughness and texture, you need the sensibility to learn what the robot arm can understand and its strengths"
CS1-005.

Accuracy and precision were the most commented physical characteristics of the robot.

The design of the task. The division of the task into three separate sessions proved successful for most participants. They felt it provides the right amount of workload while keeping it feasible, interesting and enjoyable.

"I would say to hold on to the strategy you made, of showing us first how the robot worked and afterwards giving us time to design the 'product'. It worked!"
CS1-006.

"I think this experience provided the right amount of knowledge. It was enriching and challenging, made me wish to know more, and improve myself"
CS1-001.

Naming the robot. Participants mostly gave male names to the robot (suggesting teammate traits), while three of them gave the robot neutral, genderless names. An interesting point is that participants who decided to explain the rationale behind the name were always attributing positive, human characteristics to it.

"Baymax during as in the movie Big Hero6. Baymax is a robot that cares for your health and state of mind. I thought it was appropriate"
CS1-002.

"Robin. He was very sympathetic and very helpful, like Batman's assistant"
CS1-005.

5.7.2 Barriers

Robot language came across frequently as an issue in developing a relationship with the robot. Participants noted that *"speaking the robot's language would have made the process easier and more natural"* (CS1-007) In this case participants are speaking not only about the coding and scripting parts but referring to the wider aspects of understanding robot motions and being able to translate their design thoughts into robotic movements.

Robot's physical attributes. The teach pendant was frequently mentioned as a non-intuitive device and which made communication difficult, *"I don't really know what would have helped. Maybe a friendlier interface?"CS1-007*

Translating human thought into robotic actions. In particular the motions not related to the design but that need to be included for a successful robot path (i.e. air moves)

"Sometimes the robot does whatever you want whereas in others you start feeling that the robot has his own personality"
CS1-009.

"You need to understand how the robot works, such as its movement, speed and limits before you start using it. We didn't need to change the design itself, but the way it was going to be built. I believe the harder part, after designing it, is programming the movements of the robot"
CS1-005.

Accessibility. A concern often mentioned as limiting to participants' experience is the limited accessibility to robot arms in relation to other digital fabrication machines like 3D printers or laser cutters. Even if the institution has a robot their use is limited to specialist courses and classes. This is not immediately a deterrent but is a worry going forward in their designs.

"I could visualise a lot of applications of the robot in architecture but we still need the mediation of the enterprises to have access to these machines in our day-by-day work"
CS1-009.

5.8 Summary of Results

The data analysis from the exploratory case study revealed a number of positive characteristics and barriers that designers perceive in a robotic partner and which could be relevant for the implementation of HIRC in architectural design tasks.

Positive contributions include:

- Incorporating robot constraints into the design process yields novel, unexpected design solutions which additionally can be fabricated and are scalable.
- Provides rigorous and quantifiable ways of exploring the physical design space which later allows a better understanding of the material, especially as the design evolves and needs to be shared with other disciplines.
- Exploring the design space with a robot partner forces formal geometric research to become more controlled as material and physical constraints have to be considered from early on.
- The robot pushed the participants towards new geometries that they did not think were possible and were outside of their comfort zone.
- Participants acquired a new 'machinic' sensibility to understand the robot and incorporate its characteristic into their design process. The robot represented more than a change in the tool used but a change in the approach to design. A systemic or machinic approach was required.

Major barriers were:

- Translating their design intent into robotic motions, specifically considering all the additional motions (i.e. air moves) that have to be included in the path so that the robot can successfully complete the task.
- Lack of sensors and awareness from the robot towards its surroundings.
- Lack and difficulty of access.
- The scripting language and communication protocols with the robot, including the teach pendant.
- The steep learning curve before being able to share your thoughts with it; this last one had the positive aspect that you only have to learn it once.

The next section discusses the results and implications.

5.9 Discussion of the Initial Explorations

An initial exploration was pursued to identify the main contributors towards, and barriers against, a robotic collaborative design process, and their implications. Qualitative data from nine participants involved in the implementation of an HRC design process were collected and analysed by using template analysis.

The experimental case study results support the initial hypothesis that: 1) the robot, can become a partner that augments the designer during the architectural design activity. Through the creation of a 'design environment' that integrates design, material and robotic agencies and mediated by the robotic manipulator it can accurately manipulate materials and provide feedback for the designer to evaluate and set new criteria for their design explorations by incorporating design thinking and the decision-making process. 2) Designers need to cede agency and negotiate with the robot in order to achieve significant results; however, using the symbiotic agencies of the robot, the designer and the material allows designers to explore opportunities and create new aesthetic languages.

At the same time a number of results were less expected; these included:

1. **Robots encourage designers to intellectualise their design process**. Designers rationalise that designing with a robot partner changes how they relate to the material – from a manual, intuitive way – into a situation where it does not depend on the ability of their hand anymore but in their ability to think of the design in a systematic way and translate it to the machine properly.

2. **Familiarity allows understanding**. Designers need time and testing to understand the dance of agencies and start ceding some of it to the robotic partner. As they understood the behaviour of the robot, they started to incorporate its constraints into their design thinking and allowing its behaviours to have implications on the design.

3. **Anthropomorphism**. Emotional responses to the robot were consistently positive and designers attribute human characteristics to it not only in their descriptions of the design

exercise, and naming, but even referring to the robot as ‘he’ through the interviews. Ascribing human characteristic to objects has been well studied in the fields of psychology and human–computer interaction.

4. **Technomorphism**. Vertesi (2012), describes technomorphism as the condition when participants narrate and perform their work taking the robot’s body and experiences. Embodied imagination (Myers 2008) was observed increasingly as the design exercise progressed. Participants moved from describing their designs through visualisations and 3D physical and digital models to using their bodies’ robotic gestures. Their movements supported their awareness of robotic possibilities of movement and allowed them to articulate the actions necessary for robotic manipulation (Vertesi 2012). Participants used this embodiment to collaborate with each other. Interestingly, also, when they were alone in front of their computers, it was possible to observe them moving their arm like that of the robot while designing. In this context, design visualisation and embodiment became an essential part of individual perception but also of the collective interactions between the participants.

5. **Designers like to be in control of all aspects of their creations**. Incorporating a robot into their design process encourages a shift in the agency model and requires designers to relinquish some of their unidirectional control and allow the external characteristics and constraints of matter and machine to develop during the process of becoming (Pickering 2011).

The main objective of the exploratory case study was understanding the human, robot and task factors that enable new modes of practice and connections between the different agencies. This allows speculation on the ways in which architects can redefine their role while maintaining a vital connectivity to the multiple forces, acknowledging the importance of the different actors: technique, geometry, material, and machine, in their designs. In the participants’ accounts of the exploratory case study, architects are no longer designing geometries but rather designing performances between human and non-human entities, editing their constraints, relationships, and the environments in which they evolve through the use and invention of new machinic and non-machinic agencies that operate in the physical world.

The exploratory case study indicated that the key human factors identified in the literature review are important factors for team fluency (i.e. collegiality, robot's contribution to the task, robustness, shared identity). At the same time, it revealed additional factors not captured through the literature (i.e. robot language, software and programming the robot). Furthermore, the findings point to a situation where the human factors in the developed framework cannot be seen as a discriminatory 'tick in the box' situation but as a complex network of interrelations. Factors affect each other to different degrees and the perception of team fluency depends on these relations more than on any specific element.

A follow-up main study was developed introducing sensors and an iterative feedback loop between the designer, the material and the robot with the aim of increasing the robot's participation in the design process. The software workflow from design to robot was refined. Adjustments were also made to the question guides and the participant training procedures to improve flow, and to focus more clearly on the research question of this study in identifying the implications to the different human factors. The process is described in the following sections.

Chapter 6 DESCRIPTION OF THE RESEARCH STUDY

6.1 Introduction: A Study of Human–Robot Interaction in a Collaborative Design Task

One of the fundamental problems that designers encounter when working with agents like an industrial robotic arm is that the needs of the designer are in total opposition to the needs of the robot. Whereas the design process is mainly a process of continuous speculation, iteration and the testing of ideas, robotic manipulators are for the most part tools for efficiency that need very specific problems to solve in a single, repetitive way. The process of creative enquiry requires flexibility to formulate questions and more importantly to find the right questions, whereas robotic processes thrive on finding the right solutions from very specific problem parameters. New design workflows have to be designed to enable robots to move beyond sophisticated fabrication tools and into partners that can influence the ways of generating and thinking about design. In this scenario, the change brought by robots as physical manipulators will be profound and similar to the emergence of new tools and procedures (i.e. perspective) during the Renaissance that gave birth to architecture and conception as we currently know it (Picon 2010).

This chapter is divided into two main sections following the introduction. The first one presents the characteristics of the study as a theoretically informed research study and discusses its main features. The section discusses the epistemological and methodological bases of the case study. It then further highlights the main features of the current study and introduces the research strategy and logics and methods used for data collection.

The second section describes the rationale and selection process of the design task that was devised to allow for design HIRC to occur. Material, surface forming and design criteria are explained and justified. The design task scenario is set up to evaluate the parameters that deliver team fluency as described in the theoretical HIRC framework in chapter 4 and informed by the exploratory study.

The aim of this chapter is to set the design and evaluation scenario. If robots are going to share the design studio with designers, it is important to understand the probable interactions between them. Specifically, how will robots influence and relate to designers who are not expert robot users. Will designers trust robots to perform operations that robots are capable of, without oversight? If things go wrong, will people take appropriate responsibility, or will they abdicate responsibility to the robot? And more importantly, throughout the uncertain and exploratory stages of the design process, will designers accept the guidance of a robot if it has better information? The design process is not life threatening but it requires reliance and common ground between teammates in order to find satisfactory solutions, not only at a design level but also for the human actor.

The better we understand these questions, the better we can design robots and design workflows that allow robots to be effective design partners. The exploratory study collects quantitative and qualitative information about the designer experience. The design goal was the design of a form-found concrete shell during a collaborative process between untrained designers and an industrial robotic arm.

6.2 Study Characteristics: An Interpretative Theoretically Informed Research

Here the characteristics of the current study are presented and the ANT paradigm and its epistemological and methodological concerns are discussed. The author's position as researcher and the implications of my role in the actor-network are also studied. How the world of the participants is constructed, studied and evaluated is reflected by the research paradigm and the epistemological and methodological considerations (Creswell 2007). The relationship between the researcher and the researched is established by the epistemological positioning of the research. How to investigate the research phenomenon is reflected in the methodological concerns (Creswell 1994).

Qualitative and quantitative methods are used in this research. Their positioning regarding the epistemological and methodological concerns are discussed. The discussion highlights the interpretive character of the case study presented in this dissertation from the design of the exercise, the use of qualitative and quantitative methods, the logic followed during the process of data collection and recruitment of research participants. The research takes the view that reality is socially constructed by the interactions of the different agencies acting within it.

6.2.1 Epistemological concerns

Epistemologically, there are different views of the relationship between the researcher and the researched and its effects on the research exercise. Views vary; on one side it is believed that the researcher's observations of the world can be neutral, value-free and objective (Johnson and Duberley 2000), as the researcher can detach him or herself from the researched (Clarke and Dawson 1999). On the other side it is suggested that the interactions between the researcher and the researched during the research study are conducive to knowledge and discovery (Guba and Lincoln 1994; Clarke and Dawson 1999). In this second scenario it is important for the researcher to be as close as possible to the research participants and get inside their world in order to understand their viewpoints (Clarke and Dawson 1999). Human subjectivity is acknowledged and supported. The main argument remains: should the researcher observe at a distance or closely? And furthermore, does distance provide objectivity with neutrality or does closeness provide objectivity through detailed understanding?

ANT is based on the principle of "following the actors" in order to build maps of the activities of human and non-human actants as the actor-network is built. As the researcher collects data, makes observations and performs interviews he or she becomes closer to the other actors in the network, until he or she becomes an actor inside it. In an ANT context the researcher as an actor becomes crucial in order to understand the actor-network and make informed descriptions of its process of formation. Adler and Adler (1994) describe objective and detached observation as the basis of the ethnographic method. However, the observer always interferes and even in the cases where they remain 'invisible' it is impossible to deny that the collected data is not influenced by them. Additionally, the longer the research, the more the researcher becomes a full actor in the network expressing opinions, giving advice and guiding participants. In the case of this research the constant presence and involvement of the researcher is due to two reasons: first, in order to understand and evaluate design HIRC it is crucial to access designers' thoughts and ideas during the development of the thesis design process. It cannot be expected for designers to be open about their thoughts if they do not get feedback on their intellectual, digital and physical design process. Second, in introducing a new design process to novices used to design and think in a different way, the researcher had a moral obligation to express feedback and ideas that could be of value for the participants to understand generative design techniques which they might not have encountered before. Interventions were kept semi-formal and limited to offer ideas and thoughts during discussions or casual meetings like in the corridor, at lunch or in the cafe. However, participants could request to meet the researcher at any given point if they required more specific feedback or ideas. Casual email conversations with the participants also took place throughout the development of the design exercise.

It is hard to estimate the effects of the researcher as an actor in the network. However, it could be said that conversations on the design process and its possibilities, outside the research setting, helped participants define their ideas and approach more explicitly. From the early stages, there were explicit ideas about generative, form-finding design processes and the influence of digital technologies on the architectural discourse. However, these ideas and their value outside the research setting, as well as the general approach to the design problem, became more explicit after these interventions. According to the classification of Adler and Adler (1994) it could be established that the role of the researcher for this exercise was similar to that of a peripheral-member-researcher who interacts closely enough with the human actors to establish a perspective. However, the researcher does not tell them what to do; and only acts as an insider that inspires the other actors to reflect and act for themselves (Astley and Zammuto 1992).

6.2.2 Methodological concerns

Methodologically, ANT investigations do not follow very structured logics or 'appropriate' research methods such as statistical analysis, large-scale empirical surveys or detailed laboratory experiments. What ANT literature does provide are rich descriptions of fieldwork with detailed scenes. Latour (2007, p.134-135) lists *"the three different notebooks that one should keep"* described in chapter 1.2.4 of this dissertation. Researchers have successfully used the first three notebooks to record field data in practice and analyse it using qualitative data analysis packages (CAQDAS). ANT research sees agency as distributed and for investigation purposes it aims *to "treat everything in the social and natural worlds as a continuously generated effect of the webs of relations within which they are located"* (Law 2009, p.142).

Another important aspect of ANT that affects how data is recorded is its emphasis on preserving the detail, words and actions of heterogeneous actants and its refusal for them to be substituted with the meta-language of the analyst:

> *We have to resist the idea that there exists somewhere a dictionary where all the variegated words of the actors can be translated into a few words of the social vocabulary. Will we have the courage not to substitute an unknown expression for a well-known one? We have to resist pretending the actors have only a language while the analyst possesses the meta-language in which the first is 'embedded'* (Latour 2005, p.48).

Therefore, interviews, words and actions of the actants are a very important resource to be recorded and should not be abstracted quickly. Callon (1990) emphasises the importance of these detailed descriptions. Methodologically the observer should not exercise censorship but collect all the translations without rejecting any of them a priori. Furthermore, there should not be a division between the ones that seem reasonable and the fantastic or unrealistic ones. All the actants and the relationships between them should be described, as together they from the 'translator' (Callon 1990)

A final consideration is that ANT theory seeks to write descriptions of how, rather than create interpretations of why (Wright 2015), *"it tells stories about 'how' relations assemble or don't"* (Law 2009, p.141).

6.3 Research Stage: Tasks and Procedures

Technical devices and digital fabrication tools allow for new practices and are capable of opening new understandings of matter, new ways of organising, and new complex and irregular relationships that expand material processes. These forces create new non-linear workflows that can lead to a new language characteristic of the human−robot collaborative era in architecture. A design framework was designed with the aim of foreseeing potential materialisation by integrating robotic, material and human agency in an iterative process where they are continuously influencing each other. This section describes the tasks and procedures that took place during the study.

The human study was set up for the robot to work on a collaborative design task with untrained participants**.** The goal was to collaboratively design a form-found concrete shell structure. The rationale that designing a shape together with the robot would open the possibility of establishing a bond between designer and robot. Participants were encouraged to do their own designs rather than performing the collaborative exercise on a design given to them to promote intellectual ownership over the results.

Participants were told that their job was to design a two-dimensional (2D) pattern and its resultant 3D shell structure after pop-up. A new phase-changing material technology was explored within a pop-up process, based on patterns that embed the shape into the material rather than prescribe it, allowing for an experimental approach to digital and physical design as the material exhibits *probable* but not *certain* behaviour. A novel design workflow, based on feedback loops, is proposed in building a form-finding, human–robot collaborative design process. The task entailed working with the robot during the cutting and forming of the physical version of their design. The robot would be initially cutting the pattern they designed (Figure 6-1), and then plunging it during the forming phase of the material (Figure 6-2).

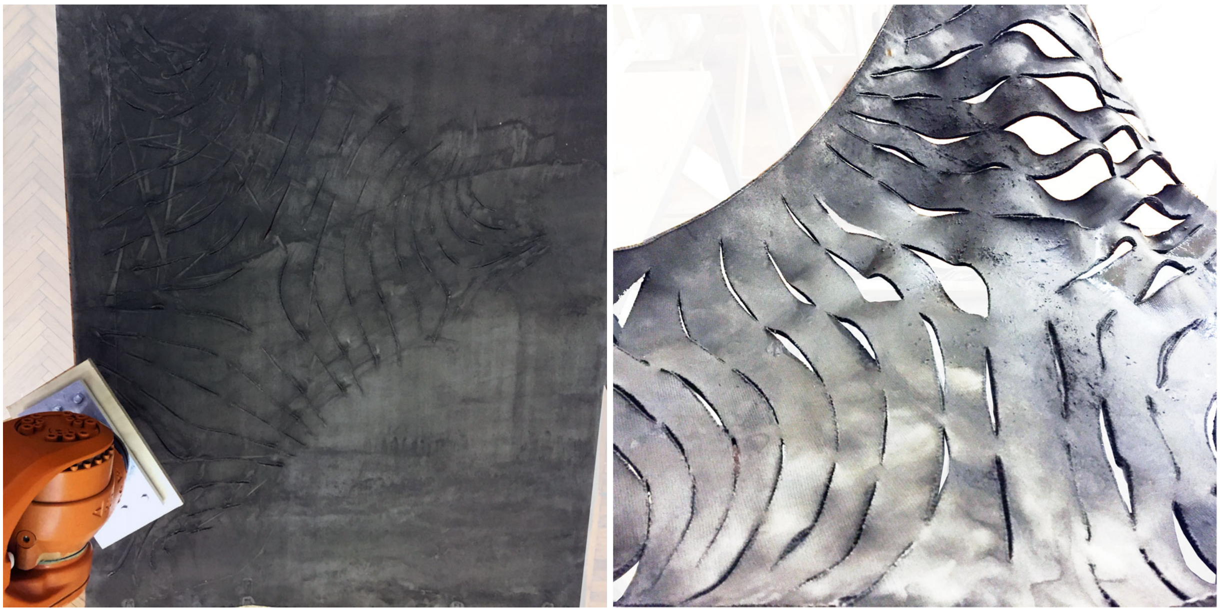

Figure 6-1 . Design process enabled by the robot. Cutting and hydrating the concrete before the forming phase

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Figure 6-2 Robot plunging and forming the material during the phase-changing stage.

Finally, it would be scanning the model during the process of formation to provide them with information about the status of the material deformation (Figure 6-3).

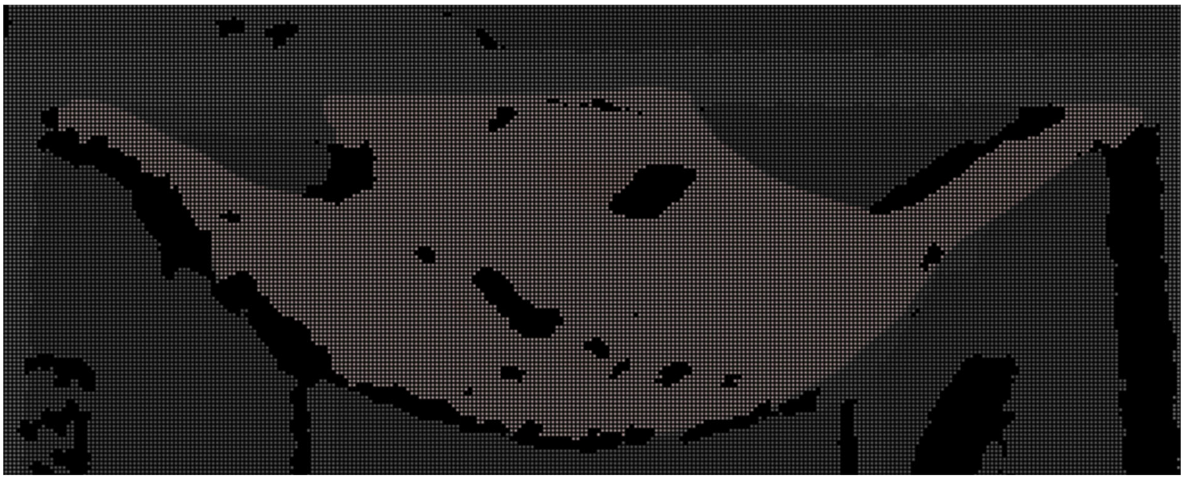

Figure 6-3 Scanning step.

The robot would be continuously comparing the physical model with the digital one and giving advice as to whether to plunge next, based on the suggestions of a software algorithm (Figure 6-4).

Figure 6-4 Comparison between the physical model and the digital design.

Based on this same framework the robot would be generating new tool paths for the next steps of the deformation. The software was programmed such that robot suggestions would always take the participant closer to achieve his or her initial desired design (Figure 6-5).

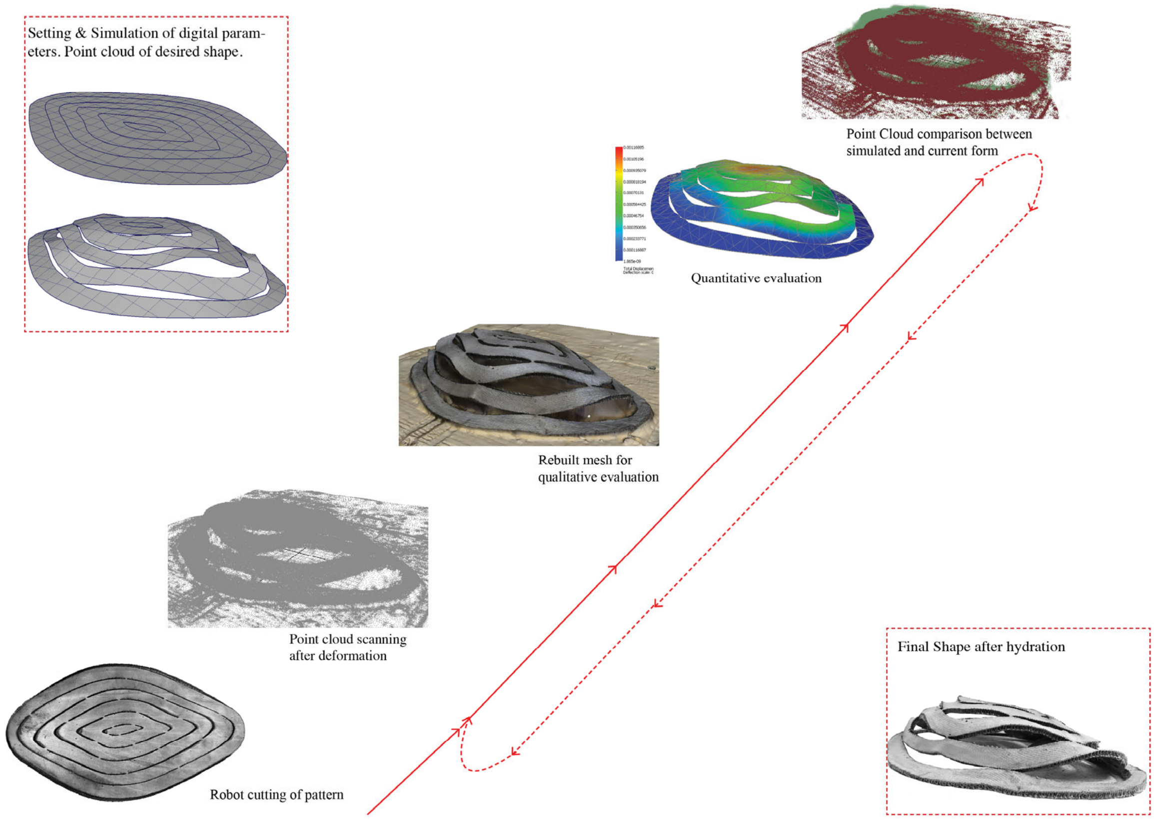

Figure 6-5 Diagram of process from physical to digital to physical to digital to physical world. The process sequence is based on boundary conditions and feedback.

The overall intent was to create a multi-dimensional design experience where the robot becomes a real amplifier of the designer's capabilities by providing additional information throughout the process. Through the iterative feedback mechanism, the relations created between the designer and the robot can be evaluated and understood. This cooperative approach to the task allowed the participant to evaluate the quality of the robot's suggestion in relation to his or her objectives. However, the robot would not be able to take any decisions and its feedback could be used or rejected by the human partner. Participants could decide on alternative plunging paths and these could be performed automatically, with the program generated by the robot, or manually by jogging the robot into the desired positions. Additionally, participants were not constrained to achieve their initial design; they could use the robot to explore alternative possibilities by manipulating the material in different ways. The design task raises the idea of working with the machine, not merely as the medium but, as an active collaborator in the process of exploration and discovery, ‘as an extension of the designer’s hand’. The computer and hence the robot then become active agents during the search of the design space, and not just the medium used to create the resultant artefacts (Lomas 2018).

Advanced Chess, a form of the game introduced by Garry Kasparov is an analogy worth exploring. Players explore possible moves using the computer. Computer chess programs can reliably and quickly detect the consequences of any proposed move. The aim is to allow human players to test potential moves with the computer assistant, making the game error-free and removing the stress of making mistakes from the human (Kasparov 2017). Through the collaboration pressure is released from humans and they can approach the game in more experimental ways. This example opens the notion that using robots more actively during the creative process could allow for a more fearless engagement with difficult ‘unruly’ generative systems, and lead designers to explore spaces with more parameters and complex interdependence between them than they would otherwise explore. Novel hybrid-agency models are expected to emerge in which the architect becomes an active agent through the materialisation process within a network where the diverse agents have equal influence on the final product (Carpo 2011).

Division of labour was established to create interdependence between the human and the robot partner (Hinds et al. 2004). The task is also designed to capitalise on the unique capabilities of the robot (i.e. translate a 3D shape from the digital environment into the physical, precise path cutting, extracting detailed information about an object shape, strength for plunging during the deformation steps), although still making sense for the human partner. Some ambiguity was built into the task to increase uncertainty and cause the participant to make explicit decisions about whether or not to rely on the robot for more than just one aspect of the task. The opportunity for errors also provided a basis on which the participant could assign responsibility and blame.

6.4 Research Strategy: Evaluation Parameters, Set Out and Criteria

The strategy for this research includes the evaluation of two kinds of variables:

- *Independent variables:* these include the circumstances or characteristics that are manipulated in the experiment to elicit a change in a human response while interacting with the robot. They are independent of participant behaviour (MacKenzie 2013).
  Device – robot arm, computer, material
  Interface – design software, robot path generator, point cloud comparison
  Feedback – visual through Kinect, tactile, visual through designer
  Human – gender, skill, expertise, study level.

- *Dependent variables:* these are the measured human behaviours and are related to any aspect of the interaction involving independent variables. They are dependent as they depend on what the participant does. The dependent variables are grouped under the overarching concept of 'team fluency'. Team fluency is formed by the four main themes of: trust, robustness, reliance and improvement. The themes and sub-themes evaluated under team fluency are described in detail in section 4.3.1.

Criteria for Success and failure

The case study and workflow are evaluated through a 36 question Likert-scale questionnaire, semi-structured interviews and scores assigned to video data and descriptive and reflective field notes. The main criteria for the evaluation of robotic assisted design workflows is to understand whether they enable or have the potential to enable: 1) interaction, does the robotic environment allow for a more interactive workflow between the designer, his or her design and its material representation which is useful and appropriate for the development of the design task? 2) Does it allow a successful integration of material behaviour to the architectural design process which can lead to unexpected solutions and novel discoveries? 3) Does it support a different way of design thinking which transforms the idea of designing a fixed geometry into designing a system?

The human–robot design collaboration will be evaluated as successful if the results are unexpected, engaging, useful and challenging for the participants in their design thinking and in their approach to the design task. The relationship between robots and designers is an intellectual one which needs to evolve in a synergetic and productive way; the themes listed under team fluency are aimed to evaluate and provide an understanding that starts to scope how designers relate to robots and which human, robot and task characteristics would make for a successful, human–robot collaborative design relationship.

6.5 Logic Used During the Process of Data Collection and Analysis

An emergent and inductive logic (Copi et al. 2006) was followed during the process of data collection and data analysis. The data collection and analysis are based on the set of relevant themes and sub-themes captured under team fluency. However, using emergent logic allowed interviews to be constructed with flexibility and awareness. Five methods were used for data collection: semi-structured interviews, participant observation, quantitative questionnaires, video recordings of the task and document analysis.

Data analysis used inductive logic informed by the theoretical resources from ANT. Following ANT, the data analysis is concerned with how the different actors interpret the design collaboration and how they feel about the idea of the robot and the material as established actors in the design process. It is important to mention that although the collaborative design phenomenon was observed from a particular ANT perspective, there was no preconception of particular outcomes during the analysis. The research avoided the use of deductive logics in which hypothesis are presented to be then tested. Hence, the theoretical framework is used as a mechanism to focus on the aspects relevant to understating HRC within the particular setting of the design process. This means that ANT moments of translation were seen as taking place within an ongoing and evolving design process rather than looking at them as theoretical categories of universal application.

This research is built on the rationale that data is created by the researcher and the research participants together (Walsham 1997). In order to address this viewpoint special consideration was given to the data collected from the interviews. It was considered as a window into the participants' reality as expressed by them; hence efforts were made to maintain the voice of the participants in the interview narrative. The resultant findings are seen as co-constructed and the interpretations acknowledged as providing a reflection of both the views of the research participant and the interests, expectations and background knowledge of the researcher (Johnson and Duberley 2000).

A mixed-method research approach, that combines qualitative research with quantitative measures, was adopted in order to identify items of team fluency and its related themes and sub-themes relevant to the design collaboration, described in section 1.4. Template analysis was used as a technique to develop a coding template for the data, described in section 1.5.

6.6 Setting out the Design Task

The task in a human−robot team, as described before, can define the success or failure of the interaction. A high degree of complexity would result in stress and overload the human partner. The design task in the research has been designed to be performed by an architectural designer who is a non-expert, novice robot and digital design and fabrication tools user. The design exercise was set up to synthesise an interactive physical/digital form-finding system, with an emphasis on the network created by the designer, the robot and the material and the influence of the last two on the design thinking of the first actor.

The digital and physical workflows were rehearsed and tested to avoid overloading the designers while keeping the design task interesting and relevant. The literature suggests non-challenging tasks as more conducive to a positive human−robot interaction. However, the design exercise requires a degree of intellectual interest that engages the designer and allows understanding of points in the design process where the contribution of the robot would be beneficial. The rationale being that an oversimplified design task would not be representative of a real scenario. Scripts, code and digital files were given to the participants with freedom to modify them and explore them as much or little as they would feel comfortable.

The following considerations were taken during the set-up:

A. The robot as an environment in which the design develops and where relationships are created between the different agencies. The robot plays different roles within this environment throughout the process.
B. A phase-changing material that allows for designer interaction and physical form-finding, within constrained boundary conditions.
C. 3D scanning device mounted on the robot end effector, which taking advantage of its capability for rotational movement allows the designer to get an overall view of the shape and also to target-scan specific points of interests and enables the feedback loop.
D. A prototypical software platform that allows for processing of the point cloud, analysis of structural stability, robot reachability, joint angles and robot-code generation.

Hybrid tectonics

In traditional architectural practice the information is derived from the design and imposed on a material (Oxman and Rosenberg 2007). In the context of the design task it is important to search for new technologies and materials that can evolve in parallel to the design process and allow for collaborative agency to emerge. Additive, subtractive and formative processes are the three main accepted material forming processes and fabrication categories (Chua et al. 2010). Traditional materials used within additive and subtractive processes can be fully simulated and anticipated making possible the whole design and fabrication process without the need for adjustments or feedback. Additionally, once the materials are formed the process cannot be reversed.

Hybrid tectonics and formative processes for materials that could allow for a symbiotic relationship between the architectural designer and the robot partner were investigated. Non-linear, forming materials allow for investigative processes where the designer can set up the various design parameters and constraints based on design intent and material properties

(Figure 6-7). He or she can then study the form and material properties by adjusting them iteratively in the physical and digital models, until a balance between design intent, technical requirements and material properties is achieved. The robot can do the physical tasks of precisely adjusting and manipulating the material, providing real-world information to the designer and analysing the retrieved data. In this scenario tasks are generated for each team member within a common design goal. The specific tasks correspond to the human and robot strengths, complement their weaknesses and offer opportunities for interaction. However, the goal cannot be achieved without both team partners.

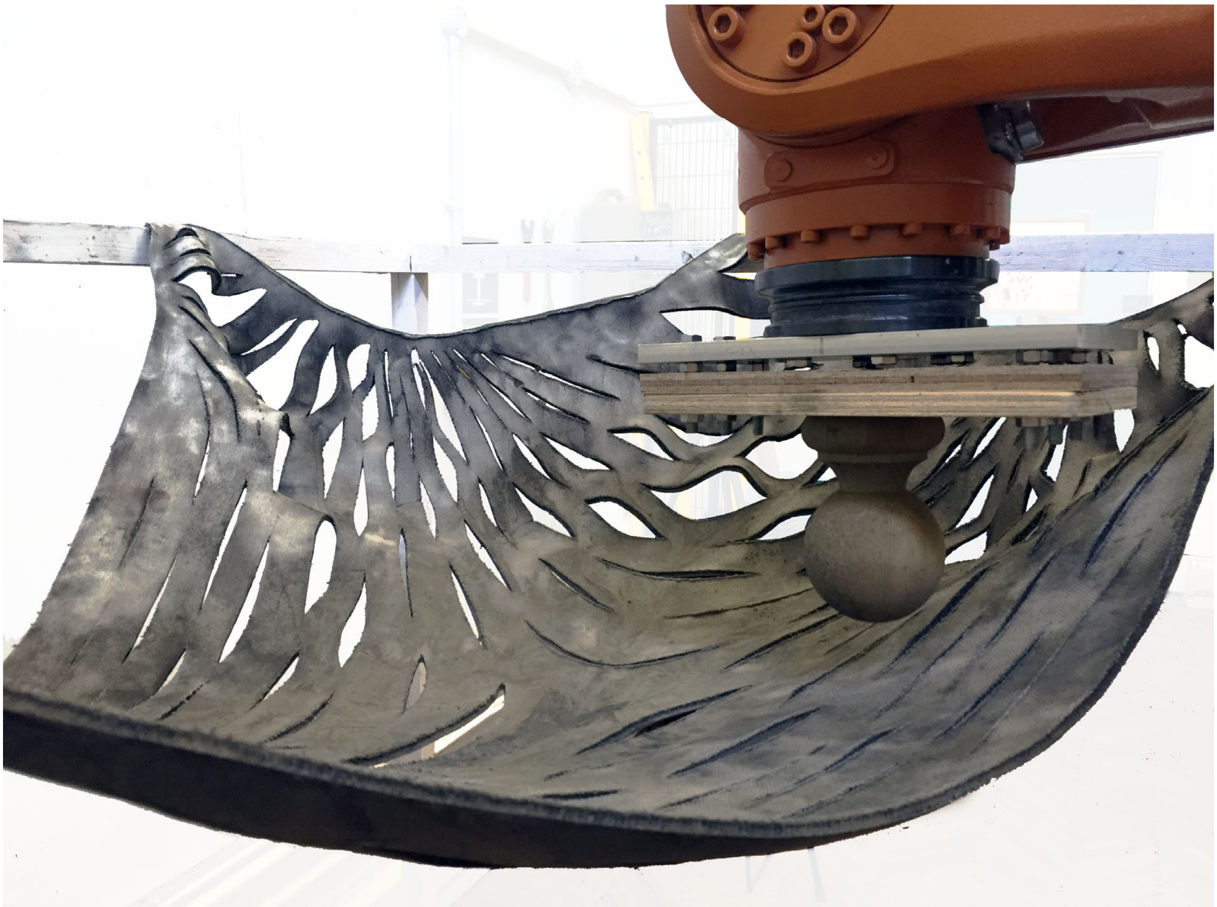

Figure 6-6 Phase-changing material during the forming step.

3D scanning device

Digital 3D scanning sensors and image capturing technologies such as Kinect, Intel sr300 have become ubiquitous, easily available and reasonably priced. They allow designers to understand material behaviour, digitalise it and abstract its properties to calibrate it with digital models. Similar to craft processes, the extracted material information can be sent back to the robot to act upon it creating a feedback loop between the material reactions, what the robot 'sees' and 'feels' and the human designer. They enable a dialogue where the robot can ask questions and expect answers as well as provide its input whereas the architect sets the objectives and constraints of the team design. Design processes where humans and robots have agency, and communicate with each other within a framework of defined tasks that encourages team fluency can accelerate the adoption of robots as design partners in architectural processes. This symbiotic relationship between architectural design and robotics opens new modes of practice moving advanced robotic technologies from fabrication tools to the genesis of the design process.

Prototypical software platform

A prototypical software platform developed in C++ is used to simulate and abstract the robot behaviour and generate the GCode required by the robot. In this same platform, robot reachability and joint angles are analysed based initially on the generated cutting paths and then on the input coordinates and digital-physical comparison during the feedback process (Figure 6-8). A detailed description of the software workflow is presented in section 7.5.3.1

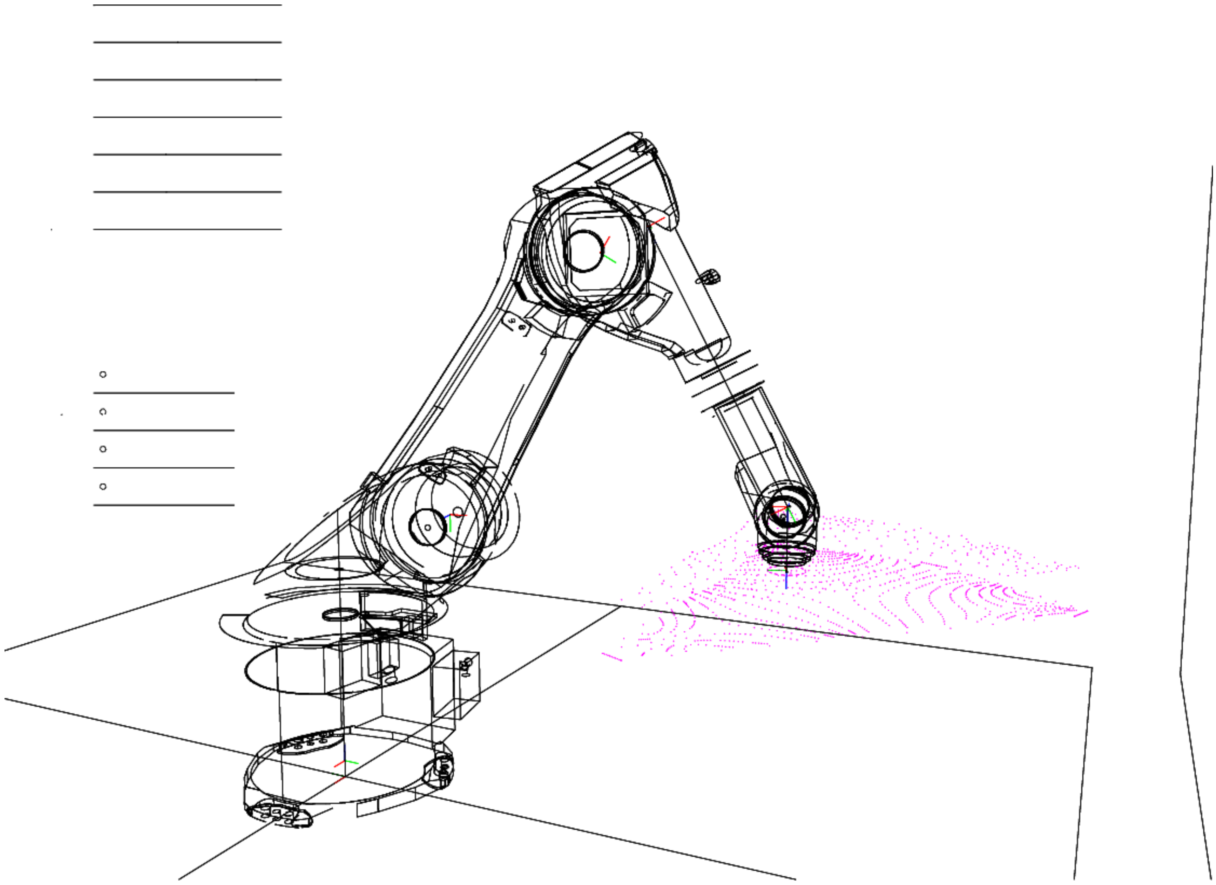

Figure 6-7 Image from IK solver with analysis of rotations and reachability for each axis.

6.7 Physical and Digital Materiality

6.7.1 Form-finding from 2D to 3D

Hybrid tectonics are explored through design geometries based on a parametric system of 2D cutting patterns performed in a phase-changing material, named concrete impregnated fabric, described below. The 2D patterns transform into extended 3D surfaces by buckling induced by spatially non-uniform, iterative plunging during the phase-changing period of the material (Figure 6-9). With the addition of water, the concrete material cures to become structurally rigid. Concrete shaping is possible as long as the concrete is in its wet state; this period lasts for three hours before it starts to settle. Digitally, 3D shapes can be collapsed into 2D cutting patterns to be popped back up into 3D surfaces.

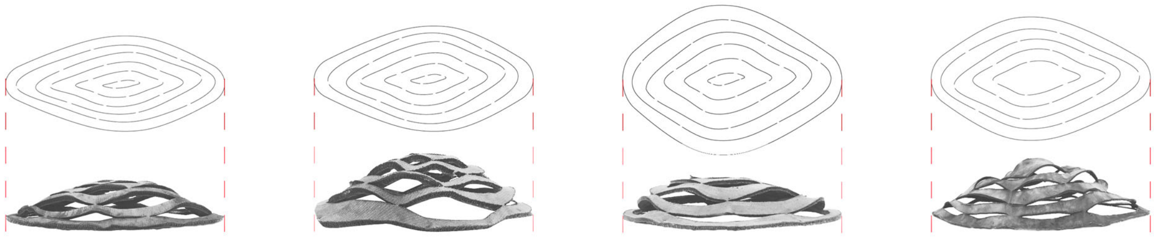

Figure 6-8 2D patterns that define the final form of the material.

Pop-up geometries are marked with a number of challenges or ‘risks’ that are not common to geometries which are first digitally modelled and then fabricated in a traditionally unidirectional process. Their generation is not random, but caused by set boundary conditions of the embedded cut and joint pattern, and follows precise physical principles during its formation. Transforming 2D sheet materials into 3D forms has been a large field of research (Menges 2016). However, proposing a design system in which designers are not directly forming a 3D shape but the parametric system to enable its creation still poses a challenge to designers not used to computational design thinking. The risks involved in this exercise were tested through prototyping. The system was converted into a clear set of rules to reduce the mental workload of participants, who have to deal with a novel design system and a robot collaborator.

The indeterminacy of the design system and the fact that through the 2D pattern and its simulation the designer can constrain the possibilities but not define the result, allow for a collaborative forming process where human and robot interact. Through the feedback loop and with defined boundary conditions the results can indirectly be controlled and emergent shapes be created by stopping the process at any point in time during the ‘pop-up’ phase of the concrete material. A main challenge of this technique is that while the desired end 3D shape is known the pattern to produce it is not, an inverse situation to that of traditional construction methods (Ye and Tsukruk 2015).

The 3D model was derived using a physics engine that simulates the behaviour of fabric material. The simulation step during the design is important for designers to understand the outcome of a given pattern and modify it accordingly. Additionally, the cutting step cannot be modified in the physical prototype, hence the importance of simulating it. The simulation can also provide a range of results that can be explored iteratively and illustrate the range of design space solutions that the designer may encounter during the material forming. After the simulation and during the physical forming process, the robot can become more than a tool as it is not working towards a single, predefined solution but exploring the solution space of the 2D pattern. The robot's input and the material deformation can influence the design thinking and decisions of the designer throughout the formation process. Concrete pop-up forming is a formative fabrication process; it allows flexibility and interaction between the human and the robot throughout the formation. The proposed form-finding process represents a search for a method using a set of tools that make explicit the importance of design as a process of continuous negotiation, enhance collaboration in architectural design and relate it to the ecosystem of design media.

6.7.2 Material selection

New materials provide an opportunity for designers to create new typologies (Thompson 2007). Material developments and higher strength concrete have been used to explore 3D complex concrete shapes that pop-up from flat 2D patterns. Concrete is not traditionally a flat sheet material. However, fabric impregnated concrete, a new hybrid material technology, combines the compressive strength of concrete and the tensile strength of fabric, blending fabric and thin shell tectonics (Figure 6-9). This seemingly contradictory characteristic allows for a more intuitive design workflow that can lead to a collaborative, flexible and adaptive design process. Additionally, the characteristics of the material change during the design process from very malleable when the fabric is in its dry state to become very rigid when hydrated, acquiring the stable properties of the concrete, allowing for a phase-changing manipulation period. Given this duality, the behaviour of the material is probable but not certain. These characteristics allow the research to assess the influence of the robot and the human manipulation and the effects of their variations during the pop-up process.

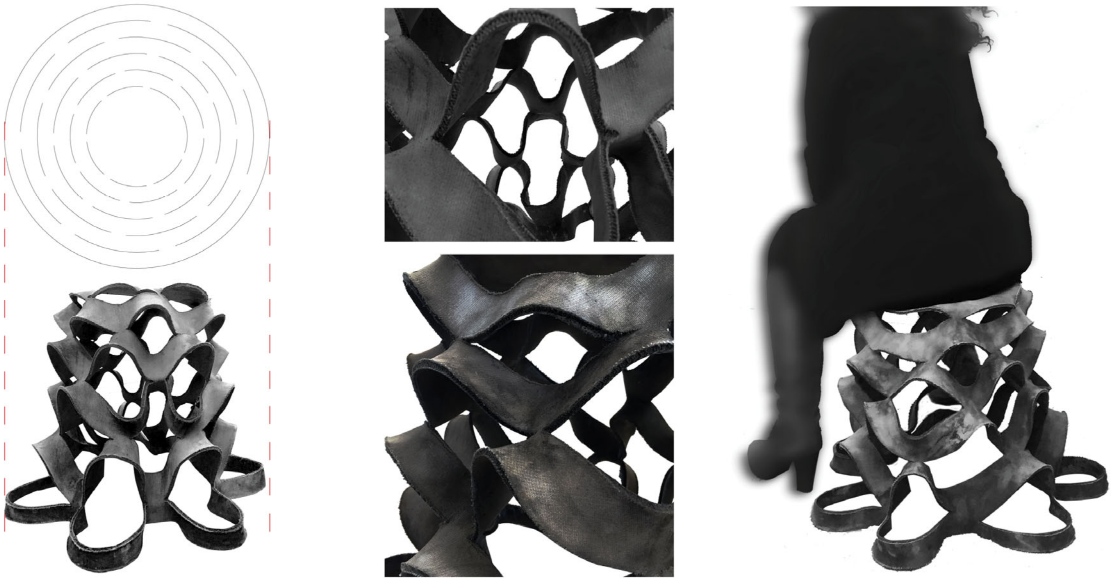

Figure 6-9 Concrete impregnated fabric rigid after hydration.

The material allows for exploration due to the uncertainties during its forming phase but is limited by real-world constraints. Through prototype testing it became clear that a feedback step is needed within the process to address the possibilities and uncertainties presented by the material when used in novel ways. The scalability of the material system is an important characteristic that allows designers to engage in the design process in a mindful way. From the initial explorations it was apparent designers understanding the HRC workflow was conducive to designs that they can apply, and not limited to exploratory, experimental processes, helped them to engage with the robot. Moreover, they felt the relevance of engaging in a robotic design process was validated when they could see the relevance of the results to traditional architectural tasks (i.e. real-world materials, form-finding processes). Through a feedback step the possibilities and uncertainties of the material are addressed and the HRC enabled. The phase-changing step allows for a relationship to form between the different agents taking part in the design task while the data is captured, analysed and next steps decided.

6.7.3 Generative design pop-up

Pop-up structures that create different 3D geometries out of 2D patterns that buckle under compression using a construction material like concrete are proposed as the generative digital and physical design system for the HIRC design task. The generative process merges computational design methods with novel materials and sensor devices that allow for a feedback loop where the collaboration between the human and the robot team members can happen.

The proposed generative design framework for design HIRC includes various steps: the designer first designs and brackets the realm of possibilities of the material through digital and physical simulations. Later, during the deployment process, the design and material are continuously analysed, using 3D scanning and robotic vision technologies, with the various agents informing each other through an interactive human−robot symbiotic process that brings human, robot and material closer together (Figure 6-10). Feedback control in this context is implemented with the purpose that the results of the latest action and its effect in the material can be analysed and used to determine the next action (Raspall et al. 2014). Through 3D scanning, material behaviour can be monitored, getting this information back to the designer allows him or her to make informed decisions regarding the initial design and manipulate it within a robotic environment that enables the iterative process to happen.

Figure 6-10 Shaping process of concrete based on a predefined pattern of cuts

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Specific tasks are assigned to the human and robot appropriate to their strengths and weaknesses (Bortot et al. 2013). During the pop-up process, decisions can be made that favour different final configurations. Decisions are informed by the information and analysis provided by the robot and the decisions taken by the designer. The forming process is continuously influenced by the robotic, human and material agencies. Team fluency will define how much agency the designer cedes to the other agents. This kind of approach changes the role of the architect to that of an editor of constraints and a designer of a system using the material and the machine. It also changes the role of the robot from that of a final fabrication machine to a team member performing actions, and providing suggestions throughout the design process. The focus is on the relationship between digital and physical actors, who can become partners without preference or hierarchy in the design process, allowing fluid movement between both worlds by negotiating boundaries and relationships.

The proposed generative design pop-up system requires the customisation and integration of different software platforms for material computing, physics simulations, scanning and point cloud manipulation and robotic control in order to be able to foresee materialisation and control it during its forming. To achieve the initial goal of enabling a human–robot–material collaborative design environment the form-found geometries need to be brought back into the digital world and a direct link needs to be created between the digital and the physical models mediated by the robot manipulator. The aim is to create a non-linear design process where the physical reality of the popped-up form will inform the digital projection and the next steps based on the designer's aims and robotic manipulation.

Chapter 7 PRACTICALITIES OF THE RESEARCH STUDY

7.1 Introduction

Chapter 7 introduces the practicalities of the study. It starts by describing the process used to gain access to the research setting. It then describes and justifies the methods used for data collection designed to evaluate the most relevant indicators throughout the design task. It describes the recruitment and selection of research participants, the interview process and ethical considerations. It then makes a step-by-step description of the task sequence. The task, evaluation metrics and data collection and preparation procedures have been designed to understand the decisions made and the actions taken by the designers working with the robot, as well as the causes driving those actions and decisions. The aim of this chapter is to describe the specific steps taken at each phase during the development of the case study.

7.2 Gaining Access to the Research Setting

The aim of this study is to understand the human and robot factors shaping a collaborative design process for non-expert robot users. This required access to a setting where these actors coexist and could easily interact. The Welsh School of Architecture (WSA), where the researcher was also involved in teaching the 'digital practises and methods' unit to undergraduate design students, offered the ideal setting and an opportunity to conduct the study discussed in this thesis. Participants would be recruited from the graduate and undergraduate School of Architecture, including current and previous students of the researcher who were familiar with her but not necessarily with any of the digital or physical design methodologies of the task. Fabrication facilities were made available to the researcher to implement the study and included the wood shop for the design and fabrication of the end effectors, shop tools and equipment. An industrial robot arm KUKA KR-60HA is housed inside a large room in the school. Adjacent to the robot room, meeting rooms for the interviews and training allowed the whole process to be contained within a small area and was easily accessible by all participants. The research study was organised to take place during the four months of the autumn term. This allows the sessions to be tailored around each participant's unique schedule.

University staff comprising the school facilities manager, director of studies, year chairs and the shop manager were contacted to negotiate use of the facilities and access to students. During conversations with the school staff the exploratory nature of the initial research question was clarified. The school could potentially also take the research study as an opportunity to introduce students to a tool like the robot arm, which normally is off-limits for students, and get valuable feedback on their interactions from the research project. This could inform the school to shape its future curriculum. Agreements were reached under an understanding that the participation will be voluntary and the sessions will be structured at the convenience of the participants so that the research would not interfere with their studies. The start of the research study was scheduled during seminar lessons at the beginning of the autumn term. This was to allow students the opportunity to allocate time for their involvement in the study at the same time that they were presented with their full workload for the term. In this way students could make an informed decision on whether to participate in the research or not. A schedule for the use of the robot arm was also agreed and negotiated with other research projects that required access to it. Further negotiations took place to use the adjacent meeting rooms and screen projector to conduct the training sessions and the interviews. Finally, a risk assessment form (Appendix D) was completed and submitted for approval. Ensuring all possible risks were covered and appropriate protection and safety materials were available on-site if needed.

7.3 Ethics Forms and Approval

Participants were informed about the aims of the study. They were told that both their participation during the task and the short interview on completion of the task would be recorded so that they could provide informed consent. The participant information sheet is provided in Appendix E. Participants were made aware that they could withdraw their participation at any moment during the development of the task without having to give any reason. Before the recorded interview participants were reminded that they could stop the interview at any point or opt out of it. Participants were given the option of answering the interview questions in writing if they were not comfortable with being recorded.

After completion of the task and for the next seven days participants could ask to withdraw their data at any point; after this time their data would be coded and analysed with that of other participants making it harder to retrieve. Participants were reassured that at all times their data would be anonymous, securely stored and maintained in the WSA and would not be used beyond the scope of this research. The experimental protocol, including health and safety regulations for material handling and robot interactions, data collection methods, questionnaires and interview formats, as well as participant recruiting methods, were reviewed and approved by the WSA in Cardiff University. The full ethics approval form as presented and signed is included in Appendix C of this dissertation.

7.4 Methods for Data Collection

This section describes the data collection methods, justified in section 6.5, and used during this study. Data was collected in four steps: 36 question Likert scale quantitative questionnaires, semi-structured interviews, video recordings of the design task, and collection of field notes. Semi-structured interviews were the main method to collect empirical data. However, quantitative information was used to complement the information given by the participants. Discrepancies observed in previous studies between participants' opinions about collaborating with robots and their actions (Charalambous et al. 2016) made the use of field notes and video recordings important sources of complementary information.

The choice of data methods used in this study was mainly influenced by their usefulness to answer the research questions. The design activity is exploratory in its nature; participants were constantly evolving their thoughts through the process and new ideas about their design aim, the robot and the collaboration were emerging. The set-up of the design exercise was focused to evaluate the aspects of trust, reliance, robustness and improvement, including the level of comfort that participants felt in working with the robot. The lack of previous research in HIRC on a design task and the lack of a guiding framework meant that a mixed-methods research approach was appropriate.

Quantitative information was useful to evaluate each of these themes and sub-themes forming team fluency in a hierarchical way according to their influence and based on the literature. However, the use of interviews and field notes became critical to examine the individual factors shaping the collaboration and participants' thoughts and opinions as they were forming. Qualitative and quantitative information has been cross referenced including field notes, interviews, questionnaires and video recordings during the evaluation process.

7.4.1 Interviews

Interviews were adopted as a method for data collection in line with the interpretive nature of this research (Creswell 1994; Creswell 2007). The knowledge from the interview is then seen as a social construct (Johnson and Duberley 2000) created through the interactions between the interviewer and the interviewee. The advantage of using interviews is that they give *"voice to the common people, allowing them to freely present their life situations in their own words"* (Kvale 2006, p.481). The interview narrative allows understanding of the actors' viewpoints from their own perspective.

Two kinds of interviews are identified based on the logic followed by the interviewer. The first type, structured interviews, do not allow the interviewer room for deviation from a structured script. This kind of interview allows the researcher to gather and evaluate data in a standardised manner (Britten 1995). The second type, semi-structured interviews utilise a loose structure based on the topics to be explored and allow the researcher to construct the interview around them with flexibility and awareness (Britten 1995). Semi-structured interviews allow diversion from the template if an area needs to be pursued more in depth. Their flexible nature allows the researcher to capture the participants' point of view without predetermining it with a selection of fixed questions, as can happen in structured interviews. They allow for emergent, relevant topics not covered in the initial interview guide, but important to the participant, to be incorporated into the conversation.

To explore the development of team fluency in a collaborative design task is crucial to elicit participants' opinions to understand how they feel when collaborating with the industrial robot. Standard interviews may miss specific areas of interest for the participants during the design development; additionally, questions would not be easily adaptable to the individual circumstances of interest for each designer. Therefore, a semi-structured interview was chosen as an appropriate tool to collect individuals' thoughts and experiences about the subject (Honey 1987).

However, problems and bias can emerge during the interview process. A disadvantage of semi-structured interviews is the possibility for the researcher's bias to emerge during the conversation and possibly guide or distort the participant's view towards a specific answer (Alvesson 2003). A method to minimise this is to use 'interview schedules' to guide participants without suggesting a specific answer and to create an adequate balance in the flow of the interview (Rapley 2012). Schedules can help the interviewer ensure that participants' opinions are expressed at all times.

Interview schedules were created, based on previous research findings and literature on HRI, which has identified robot attributes (e.g. robot performance, size, predictability, feedback, robot attributes), human elements (e.g. attitude towards robots, amount of training, etc.) and environmental elements (e.g. task complexity) as having influence over the development of team fluency in HRC . The first two having the highest influence whereas the last one has a moderate effect (Hancock et al. 2011a). The interview schedule (Appendix B) was developed with the aim to ensure that all aspects relevant to answering the research question were discussed. It was divided into the following four sections related to robot, human and material agencies and their role in the design process:

1) Robot attributes – this section focused on identifying the robot's strengths and weaknesses.
2) The robot arm in the design process – this section invited participants to analyse the qualities of the robot and how it aids or hinders their design process, including potential limitations and new opportunities. The focus being the human–robot relationship.
3) The link between digital design and physical material in the design process first and then as

enabled by the robot – this section invited participants to reflect on the connection between design and material including the making of physical models and their relevance to the design process. The focus being the material-design relationship.
4) Other topics – the final section is concerned with the participants' first reactions upon encountering the robot and subsequent relationship with it through the design exercise. This section is intended to elicit contributions, opinions and thoughts from participants in any related topic of their interest.

Additionally, problems can also manifest from the interviewee side who might be wanting to give a good impression of him or herself rather than being honest about the experience. They might also want to portray the institution in a certain way that favours them (Alvesson 2003). To avoid these problems a strategy was adopted of building trust and keeping an attitude of respect showing participants that their experiences are valuable, important and respected (Patton 2001). Moreover, additional qualitative and quantitative methods of data collection were used to compare and complement the interviews during the evaluation process.

The interviews were designed to last between 10 and 20 minutes. They were all recorded using a personal mobile phone and then transcribed. The coding template can be found in Appendix H. The full transcripts of the interviews can be found in Appendix I.

7.4.2 Questionnaires

Team fluency is a subjective construct that defines how fluent people perceive the collaboration to be. A 36 question Likert scale questionnaire was designed and administered to participants to rate agreement with team fluency notions. The questionnaire included both single statements and composites of statements related to the same measure. The questionnaire is developed and based on the literature on previous research on the field of trust, fluency and collaboration metrics in HRT. The aim was to complement the information from the interviews in evaluating the human teammate reaction to the robot, the task and to themselves. The role of collaboration between the designer and the robot was highlighted.

The questionnaire was divided into two parts:

1. A first section with 20 questions related to aspects of trust. Participants were asked to rank each statement on a five-point Likert scale going from a highly positive to highly negative statement. Each statement was customised to reflect the noun or adjective of the collaborative issue to be evaluated (i.e. highly uncomfortable to highly comfortable, very unsafe to very safe, etc.).
2. A second section with 15 statements and one open question. The questions were related to the aspects of collegiality, improvement and robustness. Participants were asked to rank agreement with each sentence on a seven-point Likert scale from “not at all” (1) to “fully” (7); an answer of (4) is considered neutral in this scale. An open-ended question at the end was related to naming the robot to evaluate attributions of gender. Researchers in the field of HCI have noted a difference in the participants’ attitude when answering closed versus open questions regarding robotic collaboration scenarios. It has been noted that robots get an increased attribution of human qualities such as gender when subjects respond to open questions (Hinds et al. 2004).

The decision to use first a five-point Likert scale and then a seven-point scale was taken because some scales assessing trust and complacency when using automation use a five-point Likert scale (i.e. Parasuraman et al. 1993; Charalambous et al. 2016), whereas other scales assessing fluency and improvement use a seven-point Likert scale (i.e. Hoffman 2013). Additionally, research shows that data is not affected by the use of five-point, seven-point or ten-point Likert scales. Furthermore, data between five-point and seven-point scales can be rescaled so that the resultant data is comparable (Dawes 2008). The full questionnaire can be found in Appendix A of this dissertation. The questionnaire was administered upon completion of the design task; it was paper based and participants were outside the robot cell with full visual access to the robot arm and the task scenario they had just completed.

7.4.3 Field Notes

Field notes were taken at every stage of the research exercise in line with ANT core principles of providing rich descriptions of the fieldwork with a specific emphasis on detailed scenes (Latour 2005). The first notebook, was used to keep a detailed account of each step, decision and questions in doing the research. It contains notes, appointments, discussion with advisers, reactions to research from others, phone calls, internet searches, etc. It encapsulates the aspects that record how the idea of the research came about, its refinement process, and the processes for finding, collecting and ordering data (Latour 2005). The first notebook can be found in Appendix K.

For Latour *"Everything is Data"*, and we need to keep track of all our moves during the research exercise (Latour 2005, p.133). He further describes a good ANT account as *"a narrative, description or proposition where all the actors do something and not just sit there"* (Latour 2005, p.128). And finally, "*a good text elicits networks of actors when it allows the writer to trace a set of relations defined by so many translations"* (Latour 2005, p.129).

However, a bad text is the one in which only a handful of actors are designated as the causes of all others which have no function and serve only as a backdrop. They will keep busy as characters but will not act and nothing is translated from one to the other. It can be concluded that if an actor makes no difference it is not an actor. Field notes were recorded with specific care given to avoid simply transporting causalities through mere intermediaries, but describing the principles of their assembly and the details that can trace back their assemblage, avoiding being only a mere description of what happened. Pierre Bourdieu describes the sociologist's task as one in which he purges himself in his descriptions of all perspectives through the extreme application of critical reflexivity:

> The sociologist must beware that: …He has a perspective which does not coincide with others, nor with the overview and over-arching perspective of the quasi-divine observer. The particularity of the social sciences calls upon him to construct a scientific truth capable of integrating the observer's vision and the truth of the agent's practical vision

> into a perspective not known which is put to the test in the illusion of the absolute. (Bourdieu 2001 in Latour 2005, p.139).

During the development of the design exercise the researcher was present with the participants at all moments observing their actions, collecting empirical data and learning with a special focus to detect the following aspects modelled on Glesne (2005):

- If the actions of the participants are compatible with their answers
- Any patterns of behaviour that might exist
- The occurrence of expected and unexpected situations for further coding their reactions to them
- Relationships developed with the robot, robot elements, task elements and with others.

The field notes can be considered both descriptive and reflective and include personal reflections and insights (Creswell 2007) during the observing period. Field notes were coded to complement the subjective information given by the participants in the interviews and questionnaires.

7.4.4 Observations and Video Recordings

Observing and recording the activities as performed by the participants and the robot were the last methods implemented for data collection in this research exercise. The video recordings were useful to look at what designers were doing and complemented what they were saying. If obvious differences were observed then the actions had to be weighted in relation to the words. Unlike the field notes that are recorded from the researcher's perspective, the video material offers objective metrics for the collaborative process. While subjective metrics from the participant's perspective on team fluency are given more weight, if objective metrics can be reliably tied in, they could become a common benchmark for evaluation of the collaboration (Hoffman 2019). Variables measured from the video recordings include safe cooperation which was measured by the distance that the participants kept from the robot, especially in the cases where being closer to the robot would have been beneficial.

A video camera was mounted at the back of room, providing a wide field of view of the robot from behind and of the faces and actions of the design participants. The material and manipulation tools were between both.

It is important to note that studies in the field of HRI have shown that when evaluating fluency it is important to draw a distinction between the fluency that is perceived by a bystander watching the collaborative interaction and the fluency experienced by the human participant in a HRT (Hinds et al. 2004). Dennett (1987) explains this as an intention-based psychology bias from humans when they are trying to interpret other agent's actions (Nass and Moon 2000). This means that for the human spectator, the goal of the action is often more obvious than the physical attributes for it, whereas for the human actor the actions might be distinctly different even if the motions and goals are the same (i.e. a person opening the door by using her right hand versus using his left hand. It could be considered to be the same action and goal for the observer, but for the person each will have very different motion trajectories and implications) (Baldwin and Baird 2001). Objective and subjective metrics are taken with the aim of quantitatively and qualitatively estimating the degree of fluency in the interaction. The field notes from the researcher's perspective and the objective observations from the video recordings are used to contrast and understand the subjective metrics from the interviews and quantitative questionnaires, however, in most cases the last two are prioritised.

7.5 Setting Out the Research

This section provides a descriptive account of the research exercise. It focuses attention on how the research participants were selected, how the material and design process was developed, providing a step-by-step description of the three sessions that comprised the design exercise, and how interviews and data were collected during them. It also discusses problems found during the set-up.

7.5.1 Selection of Research Participants

A call for voluntary participation was extended to students at the WSA. The invitation stated that students would be better suited if they are in their second year or higher as the study wished to focus on the contribution of the robot to the architectural design process. Some architectural and design training was preferred. The evaluation framework is suitable to be used by undergraduate and graduate students as well as architectural professionals throughout their design processes.

It was considered that most female and male architecture students from the second to the fifth year who responded to the call could be suitable to participate in the experiment. Participants with an enthusiasm for digital tools and participants with a critical approach towards digital tools are valuable for the evaluation of this workflow. However, it is important to note that designers have to be trained in the use of digital design tools in order to generate the geometry and robotic path. Basic digital computing skills are required from all participants in the case study to operate the robot.

The male and female group was expected to be comparable regarding age range, educational background and professional design experience to avoid any of these factors being considered responsible for observed differences. A group of 20–25 participants was expected for this case study to be able to produce significative results (Lazar et al. 2009). Controlled experiments in the field of HCI studies with fewer than 12 participants are not uncommon, but convincing results are generally generated with groups of 20 participants (Lazar et al. 2009). Consideration has to be taken for people dropping out, replacements, etc.

Recruitment was performed through the methods of placement of posters throughout the WSA, conversations with students, a general email list, and the students' association Facebook page. An incentive was offered to all the participants in the form of a day trip to London with private visits to three of the leading architectural offices: Zaha Hadid Architects, Foster and Partners, Populous and to the Architectural Association.

Students interested on taking part in the research were asked to the robotics lab. On arriving at the robot lab, participants were briefed about the experiment and given a participant information sheet (Appendix E). Participants were also asked to complete a consent form (Appendix F) and were informed that they were free to withdraw at any point. An initial questionnaire was given to all the potential participants to ensure that they were appropriate for the study. The questionnaire was used to determine their design knowledge, knowledge of digital tools, and familiarity with other automated design and fabrication tools. Other factors such as age, current year of study, experience and skills were recorded in order to generate a database of participants and ensure controlled variety within the group. To ensure anonymity, pseudonyms and a unique reference code was given to each participant. Additionally, all the participants' comments, interviews and questionnaires have been made anonymous, and the confidential documents are kept in a secure file cabinet. Ethical approval forms were prepared and submitted to the university, with the research procedure gaining approval from the same. The ethics approval form can be found in Appendix C.

7.5.2 Description of Research Material

A phase-changing material, namely concrete canvas, was selected. Concrete canvas consists of two flexible fabric membranes on each exterior surface with a 3D fibre reinforcement matrix impregnated with dry cement in-between. The top layer is a fibrous surface that can be hydrated while the back membrane is made of fire-resistant waterproof PVC (Figure 7-1). When hydrated, after 24 hours, the layers harden forming a thin, robust and lightweight concrete structure.

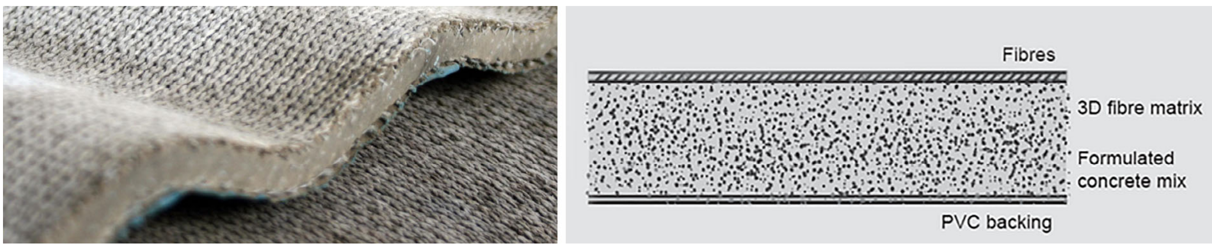


Figure 7-1 Concrete canvas composition.

Initially the material in its fabric state is very malleable. During the first two hours after hydration and before fully curing into a rigid concrete shell, the material can be modified without affecting its structural integrity and without any cement loss. It is during this phase-changing period that the designer and the robot can iteratively and collaboratively adjust and analyse the material deformation, through a feedback loop, towards a form-found formal shape objective. Through prototyping it became clear that the malleable, phase-changing period allowed for a flexible and adaptive design process, particularly, when compared to the design process of more standardised materials such as foam which can be fully simulated and anticipated and cannot be reversed after forming.

Concrete canvas is typically used for infrastructure and quick deployment of shelter structures as it only requires air and water for its construction. Shelter structures up to 50 sq m have been built using this material (Figure 7-2). The traditional mode of building with concrete canvas is by using inflation to create surfaces optimised for compressive loading. A period of 24 hours after hydration, the membranes harden forming a thin, robust and lightweight concrete structure. Concrete canvas comes in different thicknesses (5, 8, and 13 mm). The exercise in this research uses the 5 mm variety.

Figure 7-2 Traditional structures deployed using concrete canvas.

7.5.2.1 Design parameters and process

The design task consists of the design of a 2D cutting pattern of curves performed on the concrete canvas material described previously and the simulation of the resultant 3D concrete shell after iteratively plunging. The process starts with the definition of a base surface. A control pattern of cuts and joints that will define the range of possibilities of the surface form is then applied (Figure 7-3). Four main criteria that define the final popped-up geometry are identified and parametrically controlled: 1) pattern of cuts and joints; 2) plunging position; 3) plunging depth; 4) concrete hydration. The first one is defined during the digital design set-up and simulation. Steps two and three are defined with the robot motions. Pre-hydration and drying times affect both the structural rigidity of the surface as well as its elasticity. In the initial experiments, different sequences of hydration and cutting were tested to maintain the integrity of the final form and minimise concrete loss.

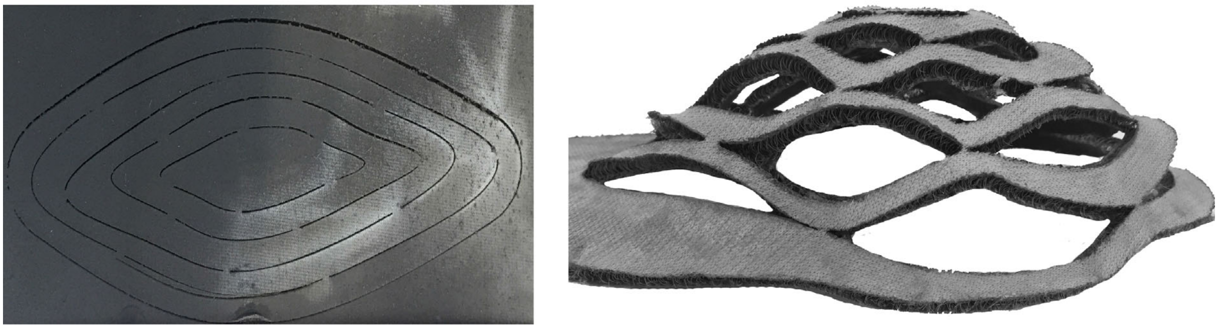


Figure 7-3 2D pattern defining the resultant shell after plunging.

The cut and joint pattern works as follows:

1. The cutting pattern: this defines the relationship between the 2D cutting pattern and the 3D pop-up geometry. On the flat material the cuts need to be offset to achieve a concave geometry. If the cuts are not proportionally spaced but clustered together the shape becomes too thin and the material loses structural integrity. If the cuts are too far apart the pop-up becomes too shallow.

2. Joint relationship: after defining the cut thickness, the next step is establishing the

relationship between cuts and joints. The joints are the areas where there is no cut and they are crucial for the popping of the unit. Joints need to be offset to produce the most rigid structural system.

The distances between the cuts, joints and the staggering between them determines the rigidity and structural stability that the final shape will have. Spatial plunging and hydration sequences will determine the final shape that the concrete will take. After the initial surface with the pattern of cuts and joints is defined and modified, it is exported to form-finding software.

The 3D model is derived using a physics engine that simulates the behaviour of the fabric material and approximates the shape digitally. Patterns are established as boundary conditions and relaxed to find the different resultant pop-up geometries within the pattern. The digital simulation step allows the designer to change the pattern until a satisfactory result are achieved (Figure 7-4). Concrete pop-up forming is a formative fabrication process; it allows flexibility and interaction between the human and the robot throughout the formation. However, the cutting step cannot be modified in the physical prototype hence making the simulation of the pattern important. Formal variations are bracketed to the realm of possibilities allowed by each cutting pattern initially defined and simulated by the designer.

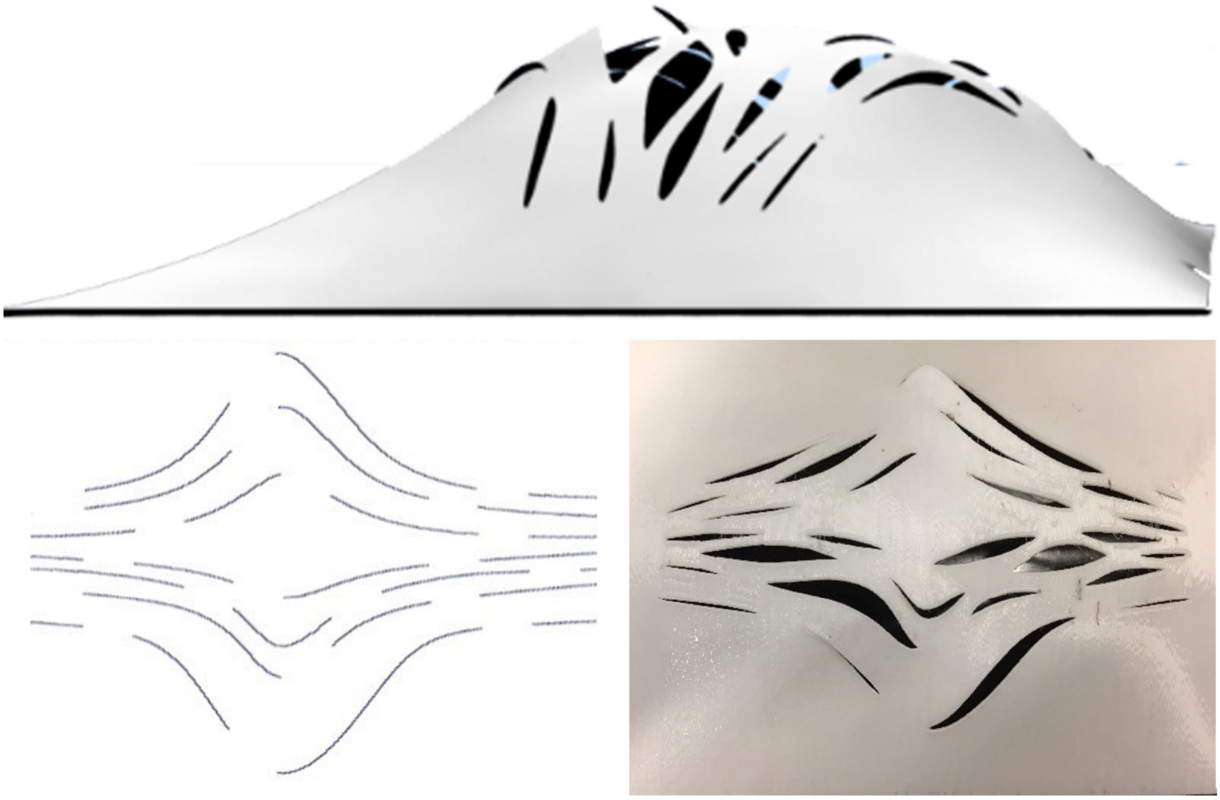


Figure 7-4 Top: simulated 3D resultant geometry. Bottom Left: 2D cutting pattern. Bottom Right: 3D print of the expected resultant form.

7.5.2.2 Popping-up

Once a satisfactory cut and joint pattern is found, the resulting data is then moved to the robot. The robot would be then used to both cut the pattern and iteratively deform it for pop-up during the curing process by plunging, and as a response to feedback from the scanned information (Figures 7-5 and 7-6).

On the physical form-finding process the plunging defines how deep the pattern extends, within its limits, deeper plunging will push the material to its limits whereas soft plunges within a constrained cut and joint pattern will result in very shallow surface deformations. The plunging has greater effects in more constrained cut and joint patterns where variations due to the plunging depth and position can be increased. Patterns with large cuts and small joints will cause larger deformations on the material immediately after hanging and due to gravity, hence the deformations due to plunging would not be so determinant. Additionally, if the joints are not evenly distributed or are too small a deep plunge from the robot can cause the material to tear changing the dynamics on the full surface.

Figure 7-5 Resultant shell after iterative plunging.

Through the feedback loop the deformation can be continuously analysed and compared, and the influence of the patterns of cuts and joints assessed as well as its variations during the pop-up process. Emergent shapes can be created by stopping the plunging process at any point in time during the pop-up phase of the concrete. The design is not finalised until the material hardens giving various opportunities, during the phase-changing period, for interaction between the designer, the robot and the material and thus making design an interactive process of co-creation.

Figure 7-6 Top, middle and bottom: Resultant shells after iterative plunging.

7.5.3 Selection of Robotic Tooling

The physical set-up includes a KUKA KR-60HA robotic arm fitted, sequentially, with two end effectors: a rotary cutter first and a Kinect with a pushing wooden sphere tool later (Figure 7-7). A set of key variables was identified for the design of the robot tool, such as the turning radius of the cuts, the depth of the sandwiched material and the robot's cutting speed. After testing different cutting tools, a 45 mm diameter sharp circular blade was selected because it allowed efficient cutting, smaller turning radii, and lower rotational speeds. Sufficient depth is needed at the entry points so that it cuts all the way through the material using a single pass.

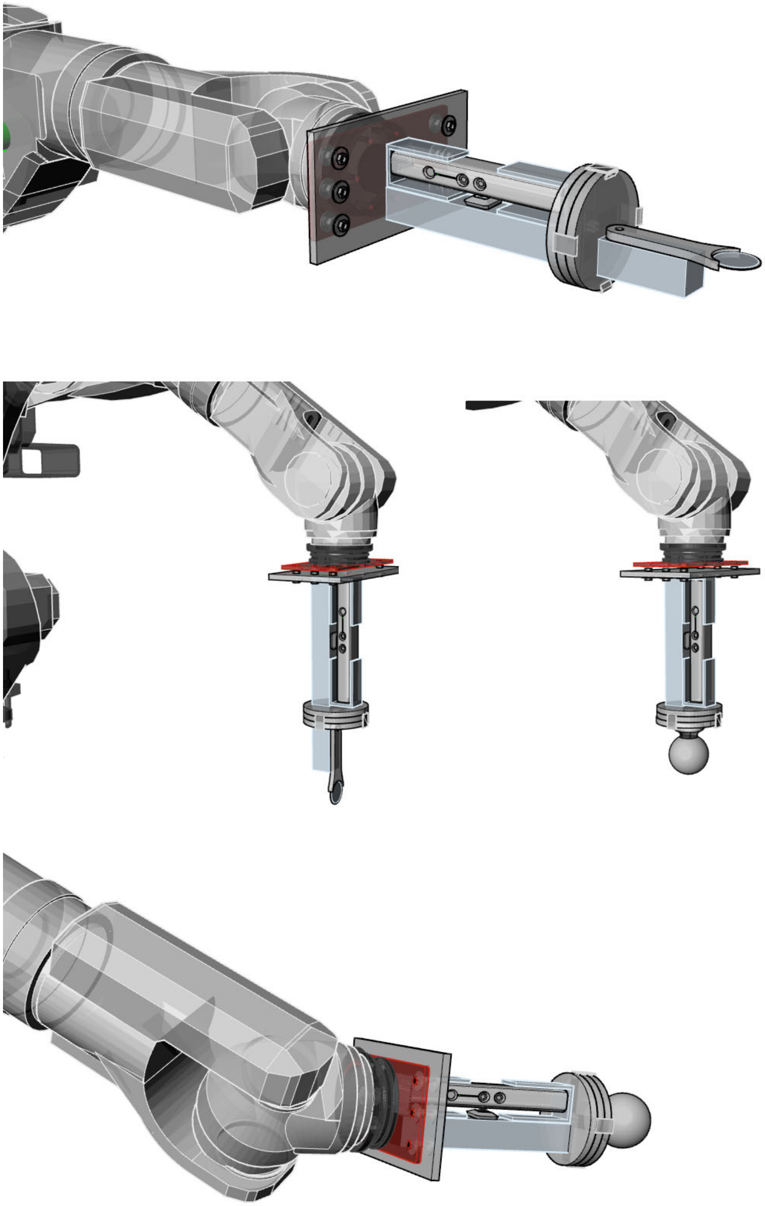


Figure 7-7 End effector detail and examples of typical use. Top: End effector with quick tool changer adaptor at the end and Kinect holder. Middle left: Cutting mode. Middle Right: Pushing Mode. Bottom: Scanning mode.

The second end effector consists of a Kinect scanning device with a 10 cm diameter wooden sphere at the end. The Kinect was used to scan the produced artefact and review how it conformed to the digital model as well as to analyse shape variations between the plunging sequences. The Kinect was calibrated to the robot and to the digital model so that designers could scan the shape from any position and compare the results either with the initial simulation or with the previous scan. The wooden sphere at the end of the end effector was used to plunge and 'massage' the concrete fabric into position. The plunging coordinates, including the depth of the plunge, will come from the digital model of the simulated shape in the initial iteration and from the comparison between digital and physical in subsequent iterations.

At each plunging position a 360-degree rotation from the sphere has been predefined. This action during testing proved useful to 'massage' the fabric and aid it in getting into position rather than just a straight plunge. The uncertainties regarding the behaviour of the concrete canvas with the applied 'cuts and joints' pattern intertwined with the fact that the pattern can allow for material extension beyond its safe limits requires continuous analysis; the continuous dialogue provides the designer with feedback of the material properties and of the deformations that are happening at each stage.

7.5.3.1 Software workflow and digital computation

Iterative digital physics-based simulations were used to gain a deeper understanding of the relationship between the cut patterns and the final 3D form. The production of low-resolution meshes using particle-spring systems is an established practice for physics simulations. They provide the designer with intuitive and qualitative knowledge during early design stages that can be augmented with structural and fabrication constraints through a feedback loop (Nahmad Vazquez et al. 2014). Calibrating a digital low-resolution mesh with the high-resolution material input from the scanning process allows the designer to work interactively with the geometry while enclosing all the important technical details such as singularity points, boundary and topological conditions, holes, clearances, etc. (Bhooshan and Sayed 2011). It also allows for an iterative quick evaluation of a range of options by adjusting key parameters that affect each realisation (Williams et al. 2011).

After the initial surface with the joints and cut pattern is defined and modified it is exported to a form-finding software based on particle-spring systems. In this case the Maya nucleus solver was used to approximate the shape digitally (Figure 7-8). The Autodesk Maya N-Cloth delivers sufficiently accurate results in replicating the material performance and pop-up behaviour observed in the physical tests as it allows embedding and calibrating different physical constraints such as damping, strength, stiffness and density. Each pattern was established as a boundary condition and relaxed to find its resultant pop-up geometry. Once the pop-ups are generated and evaluated the pattern is turned into tool paths.

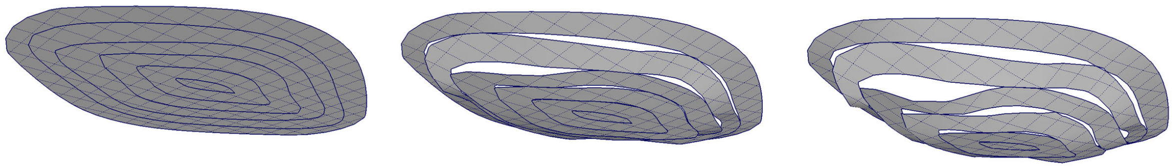


Figure 7-8 From cutting pattern definition to popped-up 3D surface simulation.

A prototypical software platform developed in C++ is used to simulate and abstract the robot behaviour and generate the KUKA KRL code required by the robot. In this same platform, a kinematic solver has been implemented which allows for the analysis of robot reachability and joint angles, the detection of singularities and control of robot behaviour (Bhooshan 2015). Paths are is based initially on the generated cutting curves and then on the input coordinates during the feedback process.

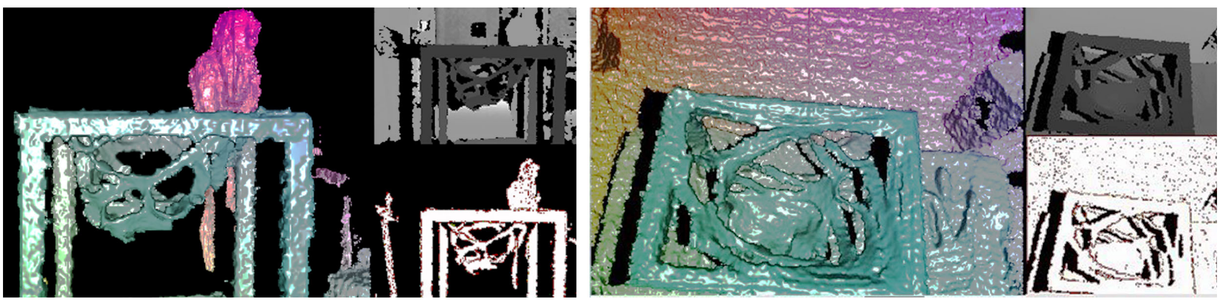


Figure 7-9 Scanning, noise reduction and point cloud for comparison, participant CS2-009.

The Kinect scanner, as described previously, is used as an external 3D scanning device, mounted as part of the robot end effector; this allows the designer to scan selectively different areas while maintaining an accurate knowledge of the Kinect coordinates. To implement a feedback loop, Processing and Simple OpenNI software (Borenstein 2015) were used to get the point cloud, centre the Kinect to the point cloud, clean and order the points and remove background noise(Figure 7-9). This information was then sent to Grasshopper in Rhino where Volvox (CITA 2016), a plugin developed by CITA to manipulate point clouds, was used to calibrate the point cloud into model space using the coordinates from the robot tool position. The obtained point cloud and the digital model were then compared and, based on the differences, a new path was created. This information was then sent to the robot platform. A 360-degree rotation after each point was added before sending the new plunging paths to the robot. The process was then repeated iteratively until a satisfactory solution was reached.

7.5.3.2 Feedback step

The feedback step involves the robot scanning and providing a point cloud representation of the existing deformed shape. The designer first selects where to scan from and can refine the point cloud interactively during the scanning process. Then the designer retrieves the position of the tool from the robot and inputs the coordinates into the Grasshopper definition that rotates and translates it to the origin of the digital model. The camera information is analysed and compared to the digitally form-found shape. The distance between both point clouds is computed and used to control future robotic motions. If the distance is within a set tolerance, no motion path is created. At this stage, the designer with the augmented knowledge from the robot can change his digital simulation, perform structural analysis on a mesh created from the point cloud or decide to implement changes to the design based on the physical model. Scanning is an iterative process aiming to match the physical artefact to the target digital geometry (Figure 7-10). The process stops when the desired form and the real shape match or are within an acceptable tolerance range.

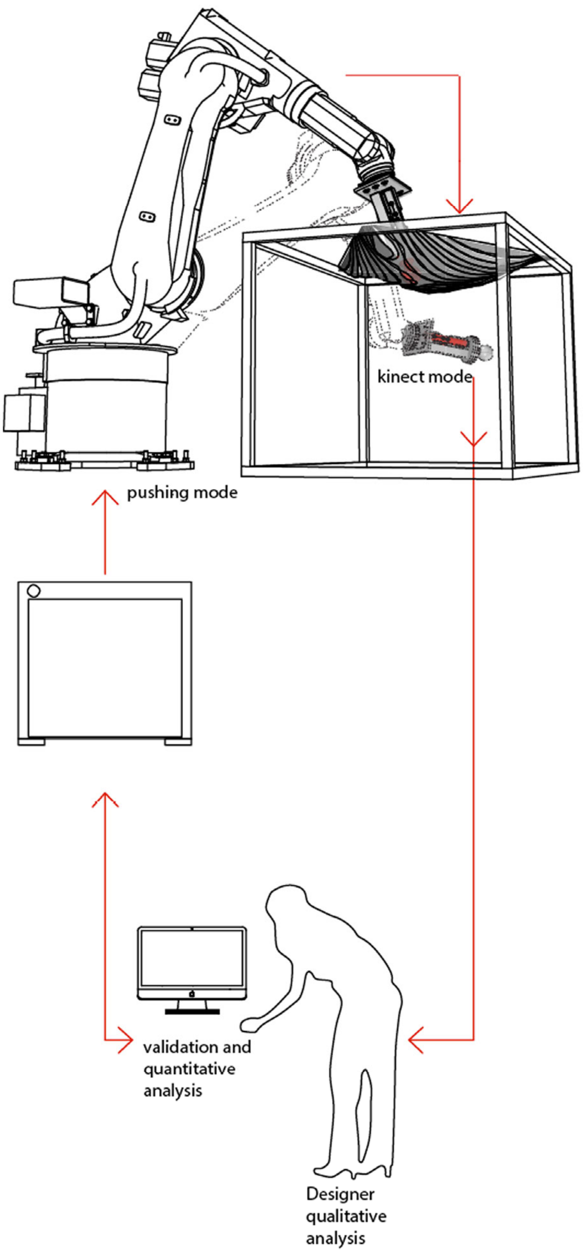


Figure 7-10 Diagram of the set-up in a wooden frame, different robot modes according to end effector and feedback loop.

The robot acts as the medium through which the designer is controlling the output and getting information about its status and performance. During the process, participants are encouraged to engage with the models and the information they are receiving to interpret and manipulate them, creating a system that *"allows for second thoughts in response to unexpected effects and* *the opportunity to recast wishes"* (Wiener in Noble 2011, p. 72). By augmenting the process iteratively, multiple physical variations can be produced to a high level of precision, which lets them be compared and evaluated to find variety, explore options and understand their formation rules.

7.6 Teaching and Demonstration Sessions: Step-by-Step Scenario

A schedule consisting of three different sessions was designed for all the participants taking part in the design task. The sessions were devised as two-hour modules to avoid overwhelming the participants and keep the interference to their schedules minimal. The sessions were planned to be individual. If participants preferred to attend in groups a maximum of four per group was established to keep them participatory. Larger groups would increase the length of the sessions and damage the data collection as different interests, backgrounds and understanding rates could interfere with the design workflow. The time and dates were open to accommodate participants' schedules and, in some occasions, sessions needed to be rescheduled due to design deadlines or personal reasons.

The design of the experiment consists of three phases. The first phase included familiarisation with the robot arm and understanding its range of movements and rotational capabilities. The second step involved recording a program of movements by manually teaching them to the robot and playing it back. After making their first programs and getting acquainted with the robot, participants start to explore the software strategies that allow the simulation and generation of suitable geometry and tool paths. Most participants were not expected to be aware of the complexity of the robot mechanisms. Instead, the process was simplified to include only inputs (i.e. design of robotic cutting paths, robot current tool coordinates) and outputs (recommendations to fix the path and the final material result). This would allow participants to focus on externalising their design intentions including the robot's parameters and limitations, to reflect critically on how to incorporate the robot, and lastly, to focus on the formal and material implications of its use rather than on the deeper technicalities of using a robotic manipulator.

Participants are not expected to become expert users in any of the digital or physical platforms. The aim of the two introductory sessions is for participants to learn how to generate a design and the main digital, material and robotic aspects that influence the resultant shape. The aim is to make the collaborative task transparent, even when the researcher has already domesticated the process for them. Previous research in the field of HCI shows that people fail to appreciate and to empathise when they do not understand what is going on (Norman 2008; Norman 2010a; Ammer 2018). Additionally, disentangling and simplifying very complex technology can also make users blind to the consequences of their decisions. Knowing the complexity behind each step can be of value to make better decisions and engage with the robot and the design as partners rather than strangers.

For the full duration of the study, from participant recruitment to the completion of the design by the last participants, the researcher maintained an open-door policy for participants. Participants who decided to work on the design task outside the sessions or would require any additional information or support could contact the researcher. Participants were advised to limit working on the task to the design sessions. The reason was to avoid any stress that the design exercise could cause if seen as an assignment. If they decided to work on the task, outside the sessions, there were no implications to the research project.

A g+ group for the task was also created to keep communication fluid between the researcher and the participants, to ask questions and to share working files, scripts and video step-by-step tutorials of the design exercise. This was also intended to relieve the pressure from participants of having to finalise the task during the session. The following section provides a detailed description of each session, including all relevant actions and concepts as were enacted by the researcher and the participants.

7.6.1 First Session: Introduction to Digital and Physical Tools

The first session of the design exercise is divided into two parts:

Part A focused on the robotic aspects of the task, including material, end effectors, and robot workflow. This session took place in the robot room.

Part B focused on the digital and design workflow: specifically, the simulation parameters and the generation of the design pattern.

First Session Part A

The session would start inside the robot cage where the robot and material elements would be explained. After the first eight participants did the session, it became clear that having the computer at hand to show them the digital robotic workflow would be helpful to increase their understanding of the process. Additionally, participants seemed to be uncomfortable inside the cage and in close proximity to the robot. The session was then restructured for the remaining participants. The revised session started with at the researcher computer desk, outside the robot cage. The explanation started with a description of the concrete fabric material that was going to be used, and a dry sample was available for the students to touch as well as the previous pop-up prototypes. The constraints of the system in terms of the cuts and joints, the dimensions, and the spacings between them for the system to generate successful results were explained and shown through the prototypes. Participants were encouraged to touch the prototypes and feel the different results from different cutting patterns. Successful and failed prototypes were discussed in terms of the 2D pattern that generated them, and how the pattern influenced the different results.

Next, the end effectors to be used and the robot were discussed. The explanation started with a general introduction to the robot and by describing how the robot was different from other digital fabrication machines that have a specific use; robots need an end effector to be designed for them. This increases the range of tasks that are available for them to perform as long as the appropriate tool is designed for them. After this, a demonstration on the computer using the purpose-built kinematic solver was given to show how each of the different axis move.

An explanation of maths and the concept of the cross product followed to show how the robot defines the position of its tool. These concepts are illustrated using a reference frame and the blade tool. The end effector, in this case, is a circular blade that has to go tangential to the curve. The role of orienting the planes aligned to the curves and in the direction that the robot needs to approach them according to the different tools was emphasised. The concept of Tool Centre Point (TCP) was introduced. After the verbal explanation, the group was shown locators the material simulation software and the robot simulator. The simulation was run to show the participants how the robot approaches the points and the differences depending the coordinates defining the orientation of the TCP.

A brief explanation of the difference between Inverse Kinematics and forward kinematics was then given to the groups. To illustrate this the researcher used hands and arms. The workflows from generating cutting curves, orientating the locators along them, exporting their positions, importing them and finally generating the robot code were shown. Participants were reassured that this was only for their understanding but all the code was going to be given to them ready to use.   The material workflow was then explained. The process of first the robot cutting the curves and how they would then hydrate the concrete fabric and mount it into the frame was rehearsed. The participants were able to see the wooden frames that had been prepared for this.

The second end effector, which consisted of a sphere and a Kinect, was shown as the tool that would first push the material into position using the sphere. Then, they would use Kinect to scan the resultant deformation by jogging the robot to their preferred position. They are shown how after scanning the point cloud would be taken into Grasshopper and through the Volvox plugin compared to their digital simulations. The Kinect was turned on during the session and the scripts that were going to be used were up on the screen. This allowed participants to scan themselves and use the script to reduce the amount of background noise. They were actively encouraged to interact with it. Most participants did not have any previous experience with any of the tools, neither digital nor physical.

First Session Part B

Once the session in the robot room was finalised and questions answered, participants and the researcher moved to a contiguous meeting room for the introduction to the digital workflow. Participants were encouraged to interrupt and actively participate in the session. They were also encouraged to follow the session by recreating the exercise on their computers, and to stop the researcher whenever they run into a difficulty.

First, students were shown a Maya file with the robot room in it and the Maya interface and tools for the task explained. Secondly, participants were taken step by step through the Maya workflow: plane creation, curve generation and rebuilding and geometry preparation for simulation. During this explanation the Maya file was described as a scene and the objects as they appeared in the outline as actors; this terminology has proven successful in the past when demonstrating the software and design techniques to students.

Once the students had a set of curves – to their liking – they get cleaned and the history was deleted. As a last step, the plane was made into an N-Cloth. The settings for the N-Cloth deformation and digital-physical material approximation were shown.

The session concludes by asking the participants if they had any questions and providing them with the two Maya files: one with the robot room including the location of the table, and one with the parameters for the N-Cloth nucleus solver simulation. A power point presentation that described the process step by step was also given to them. Participants could stay to do their design in the room with the aid of the researcher or could leave to do it in their own working place.

7.6.2 Second Session: The Robot

"in teaching a robot what to do, the novice is simultaneously learning more about the machine and about how to better communicate with it" (Lim 2014, p.173).

The aim of the second session is to start creating a relationship between the human and non-human actors involved in this research. Human actors were physically introduced to their non-human partner. This session happened inside the robot cage and took between one and two hours. It could be considered a light introduction to robotic arms.

The session started by inviting participants inside the cage. The teach pendant and all its buttons were explained as the main communication tool between the humans and the robot. A description of how robot moves can be recorded, manipulated and controlled from the teach pendant follows. Emphasis was given to the dead man switch, the play button and the panic button. After this, the different jogging modes were explained and how the reference frames change depending on which one was used. A pen was set up as end effector so that the different motions were visible and could be understood. Participants were encouraged to jog the robot, and test the different jogging modes to understand motion types (Figure 7-11).

Then, an explanation was given on how to record a program. Targets were placed on the table for the robot to reach. From the results in the exploratory case study, it was emphasised that the moves that they made to reach a target might not necessarily be the moves that the robot would do to reach those same points, unless explicitly recorded. Participants were finally asked to record a program; they could use the targets to try to reach them in different angles for their program, or do an alternative path without them if they preferred. Once the program was recorded participants would run it on teaching mode. After playing their recorded program, the participant and researcher moved outside the cage where the safety features were explained. Participants could then run their programs in automatic mode.

The aim of the session is to get the students familiar with the robot's motions, physical appearance and traditional control mechanisms (teach pendant), even when they are not the main robotic programming tools for architects. Participants were allowed to practise and jog the robot for an unlimited amount of time.

Figure 7-11 Participants jogging and positioning the robot.

7.6.3 Third Session: Popping up the Concrete or Conducting the Design Exercise

The last session is about the design exercise. This session was scheduled once the participants had completed the previous two sessions. At this stage, their control pattern of cuts and joints was designed and iteratively refined during the simulation process. Participant would arrive with their 3D design and the pattern that produced it. The physical form-finding process aided by the robot would then start.

The first robot intervention consisted of cutting the selected pattern into the material. Next, the end effector was changed and the forming process started to create the chosen form. The forming process consists of an iteration of four steps. The first step includes fixing the material to a wooden frame where the edges of the concrete sheet are constrained in the *x* and *y* directions but not in the *z* direction. Within the set limit, the robot force is used to push the fabric and start the deformation process. The second step involved the robot scanning and providing a point cloud representation of the existing deformed shape.

The designer first selected where to scan from and can refine the point cloud interactively during the scanning process. Then, the feedback step starts (section 7.5.3.2). The process is iteratively repeated and only stopped when the desired form and the real shape match or are within an acceptable tolerance range. The designer could also choose to go in a different direction through the form-finding process and end with a shape completely different from his or her original intent. The final shape is independent from the iterative feedback (i.e. after each feedback step designers had freedom to decide how to proceed).

A step-by-step description of the session is as follows:

1. The participants' code for cutting their design paths had been tested in advance by the researcher and was loaded into the controller. Participants' relaxed mesh as a final design target was also already loaded into the 3D software Rhino model. The digital file was calibrated to the physical position of the hanging frame for the concrete cloth.

2. Participants cutting a rectangular piece of the concrete canvas, and positioning it on the table to be cut by the robot (Figure 7-12).

3. Robot cutting the participant pattern into the material (Figure 7-13).

Figure 7-12 Participants cutting the concrete.

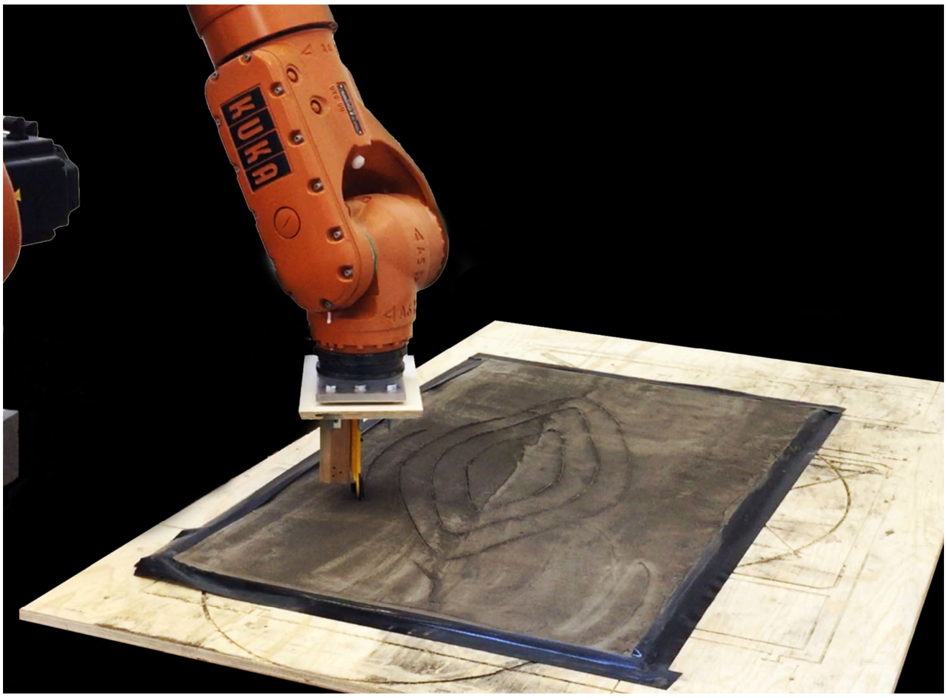


Figure 7-13 Robot cutting the concrete

4. Participant and researcher going inside the cage. The researcher changed the end effector on the robot from the knife to the Kinect scanner and plunging sphere. Making sure that is in the correct position and orientation that corresponded to the translations and rotations for the digital model during the comparison steps. The participant hydrated the concrete fabric until fully soaked using the spraying bottles.

5. Participant fixing the material to a wooden frame where the edges of the concrete sheet were constrained in the x and y directions but not in the z direction. Within the set limit, the robot force was used to push the fabric and start the deformation process (Figure 7-14).

Figure 7-14 Participant fixing concrete to frame and starting the physical form-finding process.

The participant had the option to do an initial scan before any plunging was done, or to send the initial plunging path to start the concrete deformation. Participants could jog the robot and select the position from which they want to do the scan (i.e. side, top, front, etc.) (Figure 7-15).

Figure 7-15 Scanning step.

The scanning process worked as follows for all the scanning iterations. Participants manually positioned the robot in their preferred position to do the scanning. They could see on the computer what the scanner was seeing – through a processing script – and select different views (Figure 7-16). Then, they could remove the background and keep the parts that they are interested in comparing; this can be as focused as the participant selects. When the participant was satisfied with it, the scan was recorded through a key press function and the .txt file of the point cloud was then sent to Rhino and a Grasshopper definition for comparison.

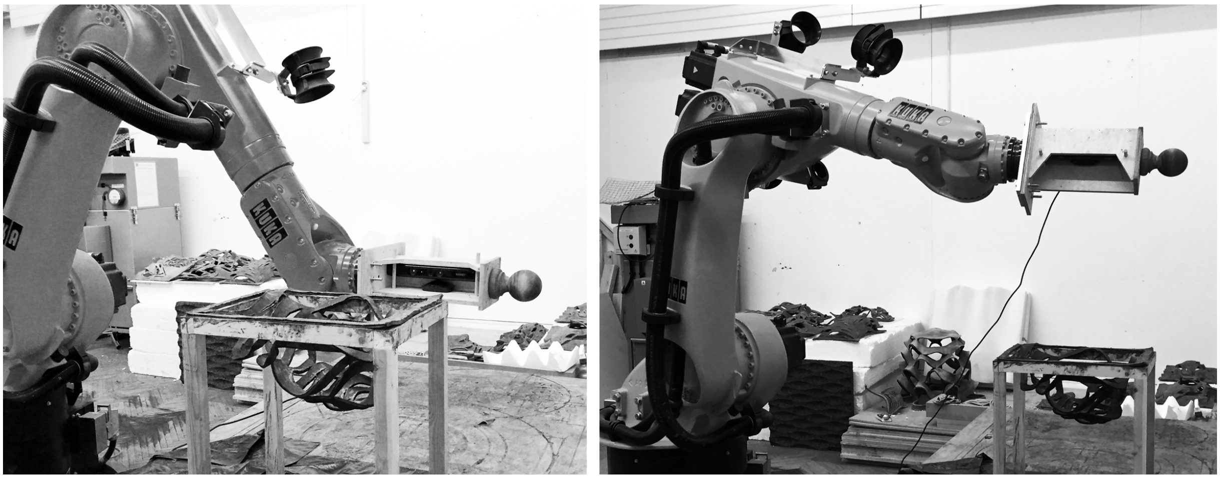
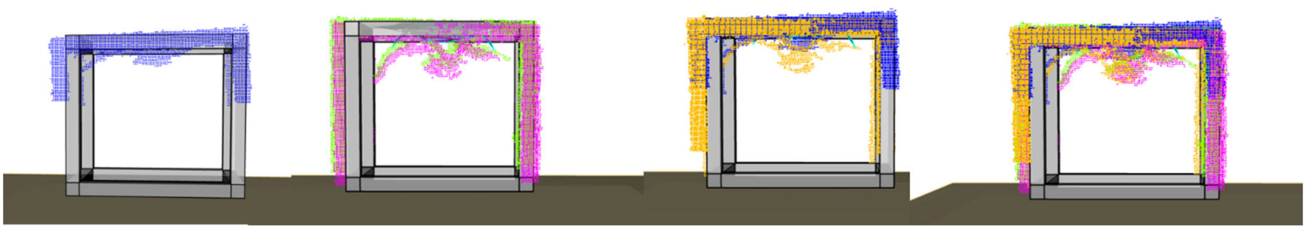


Figure 7-16 Participants scanning their models.

Participants then use the coordinates of where the point cloud was recorded – relative to the robot and end effector – and the point cloud can then be translated and rotated in the model space to the position of its digital twin. The whole process was done in less than a minute. A comparison was then made between the recorded point cloud and the digital design or 'target' shape. The points where the shapes were not matching were then isolated and converted into new robotic paths for the next plunging iteration. Each plunging iteration includes a 360-degree rotation at each of the points so that the robot 'massages' the shape into position.

6. After the participant scanned the shape, and a new robotic plunging path was generated; participants could then decide to run this new path program either in automatic or on manual mode (through the teach pendant). Participants were encouraged to hydrate the shell during the rotation of the plunging sphere or before starting each plunging iteration (Figure 7-17).



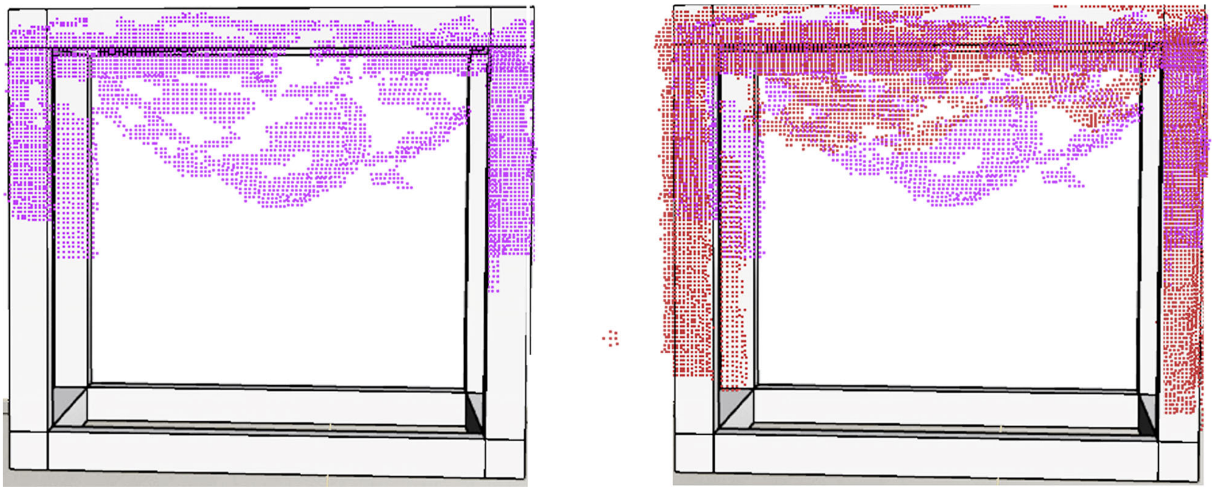


Figure 7-17 Comparison between the different plunging iterations, the desired and simulated digital shape is 85%match at the end of the process.. Participants were satisfied with the results. Participant CS2-001 and CS2-011.

7. Participants could repeat the plunging and scanning steps (Figure 7-18) until they were satisfied with the results. They could also do further pushing iterations by manually jogging the robot if preferred (Figure 7-19).

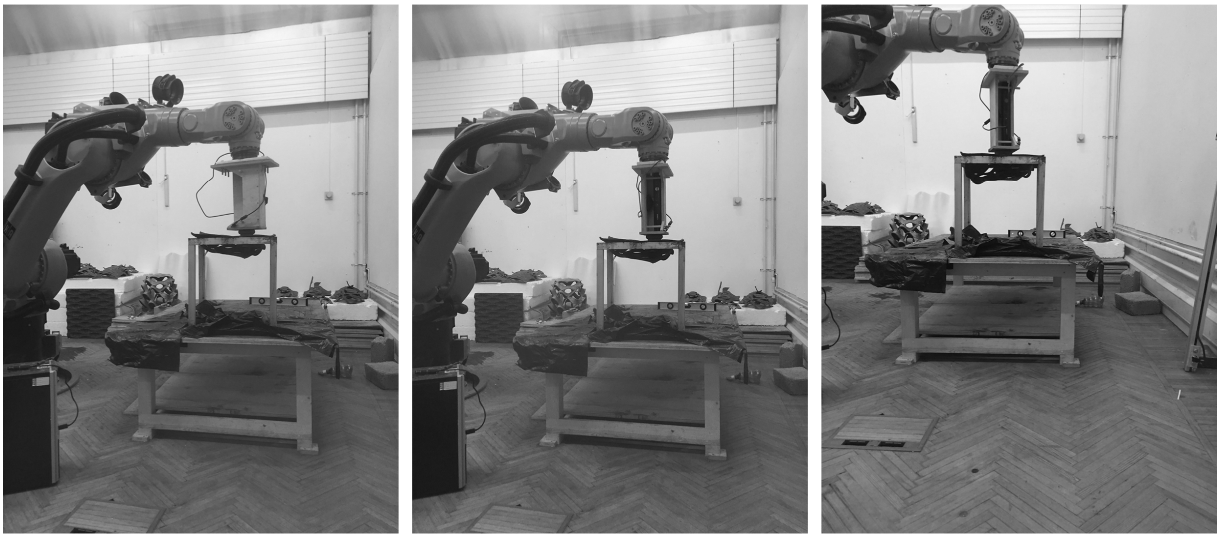


Figure 7-18 Plunging step, including rotation and material massaging at teach plunge.

8. Once participants were satisfied with the shape, a final scan was made to record the result and any deviations from the initial design objective. The fabric then got a final round of water to ensure that it was completely wet before letting it settle (Figure 7-20).

Figure 7-19 Plunging and hydrating sequence.

The pace of the task was determined by the participant design intent and interests. The design session took between two hours to four hours to complete depending on the level of engagement between the participant and the design procedure. During the whole process, participants were observed and technically assisted by the researcher. During the design session participants were video recorded using a camera positioned in the back corner of the room, behind the robot.

Figure 7-20 Last plunging iteration and concrete fully hydrated, ready for settling.

Once the design exercise was complete (Figures 7-21, 7-22), participants came out of the robotic cage and completed a 36 item Likert scale questionnaire. The questionnaire was completed on paper and on a desk from which participants had visual contact with the industrial robot. After completing and submitting the questionnaire, participants moved to a post-task semi-structured interview conducted by the researcher. Interviews were recorded using the voice memo function on an iPhone. Before starting the interview, participants were reminded that they could withdraw if they did not feel comfortable. An option to answer the interview questions in written format was offered to participants who did not want their voices to be recorded. This concludes the design task. Participants that were interested in returning later to see how their shell turned up and take images were encouraged to do so.

All the instructions given to the participants were phrased and told so as to imply the importance of the team as a joint performance entity, especially during the forming and feedback loops.

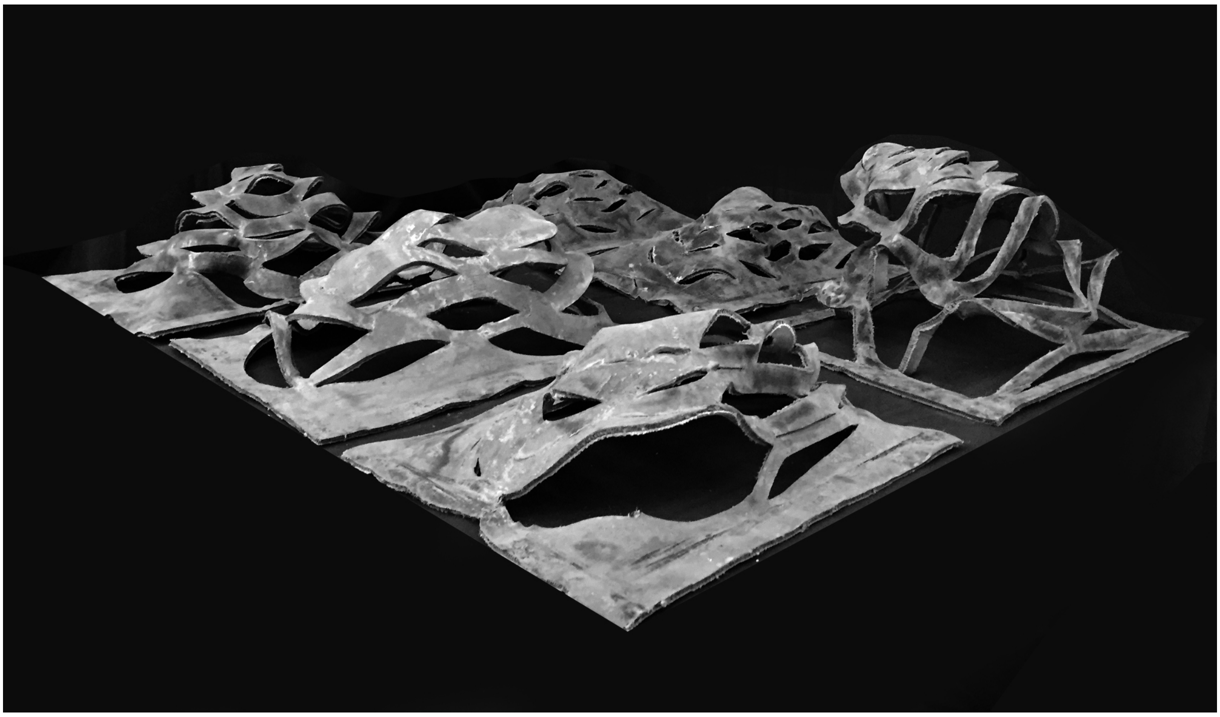


Figure 7-21. The boundary condition was the same for all. The pop-up pattern was designed and decided by each participant as well as the deformation during the process. The result could be different from the simulation.

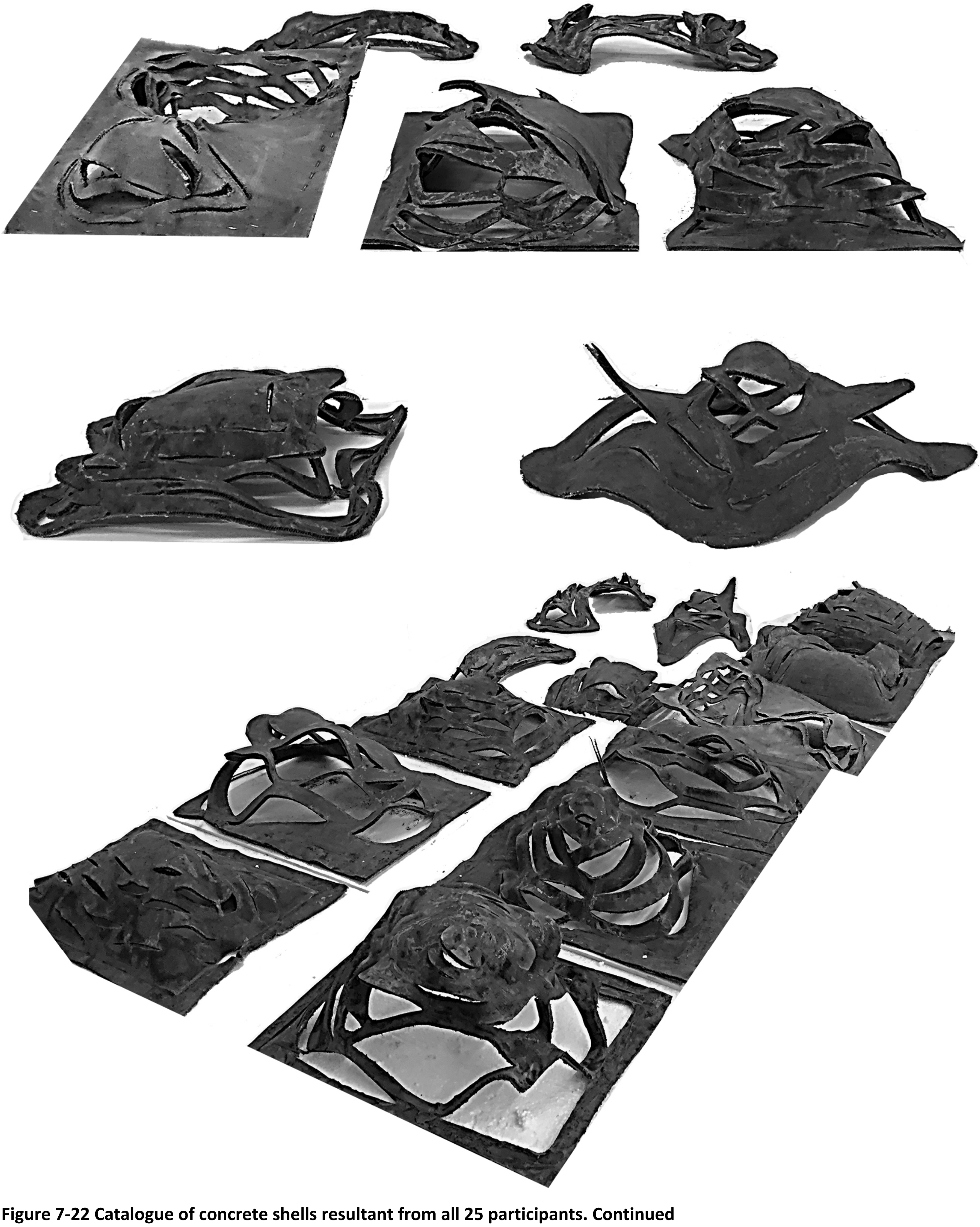


Figure 7-22 Catalogue of concrete shells resultant from all 25 participants. Continued

7.6.4 Problems During the Design Set-up

Initially participants had technical problems exporting their curves and generating robotic paths using the scripts given to them in their personal computers. Participants were asked to send their designs in advance to the researcher. In this way, all technical problems could be resolved in advance and the researcher would have the set-up ready for the arrival of the participants. This in an effort to maximise the session time with the participants allowing them to focus on the human−robot collaborative process, rather than in resolving technical problems.

In the initial set-up there was a concern that if students did not generate their own designs, they would not feel ownership over them and hence the collaboration would not be as significative. However, further researcher suggested that in design teams the individual designers feel ownership over the collective results as long as they remain involved in any form during its generation (Loukissas 2012). To avoid overloading participants and to allow them to complete the design task while retaining a sense of ownership over it, the researcher asked participants who indicated finding it problematic to generate their designs due to their academic workload, to describe what shape they were imagining and to do a quick sketch of the curves and the shape of the curves that they wished to create. It was agreed that the researcher would develop shapes and patterns on behalf of the participants while they remained involved in the genesis of the design. Participants would sketch and describe their designs as wanting 'avocado' looking curves or an elongated like a 'bean' etc. However, a new code was introduced to separate participants who did their design from those that had it done for them, and then compare the two categories to determine if this had any effect on their sense of ownership, attribution of credit and blame during the development of the task.

7.7 Catalogue of Human and Non-Human Actants Present in The Design Exercise

A list of all the actants, as defined by Latour (human and non-human), present for the development of the design task and which could influence its development is provided below.

Human designer: An architect or architecture student and non-expert robot user.

Robotic arm manipulator: KUKA KR-60 HA 6-axis robotic industrial arm.

Concrete phase-changing material: Concrete canvas material on which to cut a generative pattern of cuts and joints when soft and hydrate while forming to achieve a hard-concrete shell.

Physics solver simulation software: Software where participants could test their 2D patterns, predict their design results and refine them

Kinect end effector: An end effector consisting of a Kinect camera cased in alignment to the centre of the flange of the robot so that the origin of the point cloud and the position of the flange can be easily aligned. The end effector has a 10 cm radius wooden sphere at the end which the robot will be using to massage the cloth at each plunging position. The case around the Kinect is tightly fit and cushioned to prevent it from coming off during the robot's moves. This means that the Kinect can be upside down over the shape; or in any position selected by the participant without the Kinect moving or falling down.

Cutting end effector: This end effector consists of a wooden panel with a 2" x 2" pole attached to the centre. On top of the pole a rotary cutter with a circular blade is tightly fixed. A casing protects the blade and a protection sleeve is used to cover the blade when not in use.

Wooden Frames: Seven wooden frames, made of 2"x 2"'s, are used for the participants to hang the concrete for the plunging iterations and for drying. The plunging end effector and the digital feedback is calibrated to the size of the frames.

Grasshopper definitions: Two Grasshopper definitions are prepared for the participants' feedback and plunging steps:

1) For the initial plunging step, the definition takes the mesh resultant from the participants' design and creates a series of plunging points on top of it for the robot to plunge and deform the concrete cloth. At each plunging point a 360-degree rotation of the sixth axis is integrated

to 'massage' the fabric into position.

2) The second one relates to the subsequent plunging steps. It takes the point cloud from its origin point, and translates it to the position in world coordinates of the wooden frame on top of the table. The mesh from the original simulation and the point cloud from the scanning step are then compared. A set of points is generated from this comparison indicating the areas where additional plunging is needed to achieve the desired initial shape. It then generates the 360-degree rotation around each point so that the robot 'massages' the fabric into position at each plunge. The steps on this definition are repeated iteratively until the physical model and the original design match or until the participant is satisfied. Two scans are encouraged as a minimum but there is no upper limit on numbers of scans.

MEL scripts: One Mel script has been prepared for the participants to generate the cutting paths. This will be used on the first part of the design exercise to convert their curves to coordinates and then to robot code for cutting. The script first adds locators tangential to their curves, based on a custom specified number of spans; It then takes the start and end point of each curve, duplicates the locators and moves them up on the 'Z' direction to generate the air movements for the robot in-between cuts. Finally, it exports the plane coordinates of each locator for the robot position and orientation as a .txt file.

Purpose made robot Kinematic solver: A purpose made kinematic solver was created in C++ to process the input points and generate the KRL code for the robot, described in section 7.5.3.1.

Processing script: One processing script has been generated for the participants to scan their concrete cloth from any angle. The script will then remove background noise and shift the centre of the scan to the centre of the camera from where it was taken. It then exports the point cloud as a .txt file to be read by the Grasshopper point cloud comparison script.

7.8 Conclusion

This section has introduced in detail the design of the research exercise, and data collection methods to answer the research questions of the study. Participants were interviewed and questionnaires collected. To contextualise and clarify some of the subjective data collected, other qualitative and quantitative methods such as observations, video recordings and field notes were used. The use of multiple methods provided the opportunity to present a chronological narrative of the implementation and conceptualise how the collaborative framework was introduced into a design exercise as a means to create a collaborative environment where human, robot and material agencies collaborate and continuously inform each through the form-finding and design discovery process.

The research exercise and its practises are made transparent and the actors participating in the collaborative framework are unfolded. The following chapters introduce the implementation of the HIRC research exercise, data analysis methods and their findings, in which theoretical resources from ANT were used.

Chapter 8 DATA ANALYSIS OF THE RESEARCH STUDY

8.1 Introduction

The purpose of this section is to provide a descriptive account of the research study as it happened. It focuses attention on the process of data analysis. The empirical data was collected through different qualitative and quantitative methods. This section describes the procedure followed in the analysis of both types of data, first individually and then integrated for the interpretative phase of the study. The two types of data are compared and used to complement and contextualise each other before reporting any findings in chapter 9. What participants said was informed by what they did and the specific circumstances that might have arisen during their individual collaborative design exercise.

Participants

A total of 25 participants took part in the case study in WSA at Cardiff University: 12 female and 13 male. The age range of the participants was between 18 and 29 years with a M = 20 and SD = 2.26 (Figure 8-1).

Participants were in their second year of study (n = 17), in their third year (n = 7) and postgraduate students (n = 1) (Figure8-2).

Eight participants reported not having any experience with any digital fabrication machines while 17 reported having some experience with digital fabrication machines. The laser cutter was the most popular with 15 participants having experience with it, followed by the 3D printer with nine participants reporting some experience with it. Computer numerical control (CNC) milling and routing machines had only been used by three participants. A total of 22 participants reported not having any experience with robots while three reported having some experience with them.

A total of 13 participants designed their shape while 12 asked the researcher to provide a design for them. There were no indicative differences between participants with previous digital experience and their engagement in designing the shape or not (Figure 8-3). Designing the shape as a variable was expected to have an impact on participants engagement during the physical form-finding process. However, the results show no significative differences in the level of engagement with the design task and its output between participants who were actively involved in the genesis of the shape and those who got the design with its digital simulation from the researcher. Nevertheless, this is kept as a parameter for the cases in which participants became very attached to their designs. Which could show as being less open to accept variations during the form-finding process and reacting negatively to changes occasioned by the robot during the formation process.

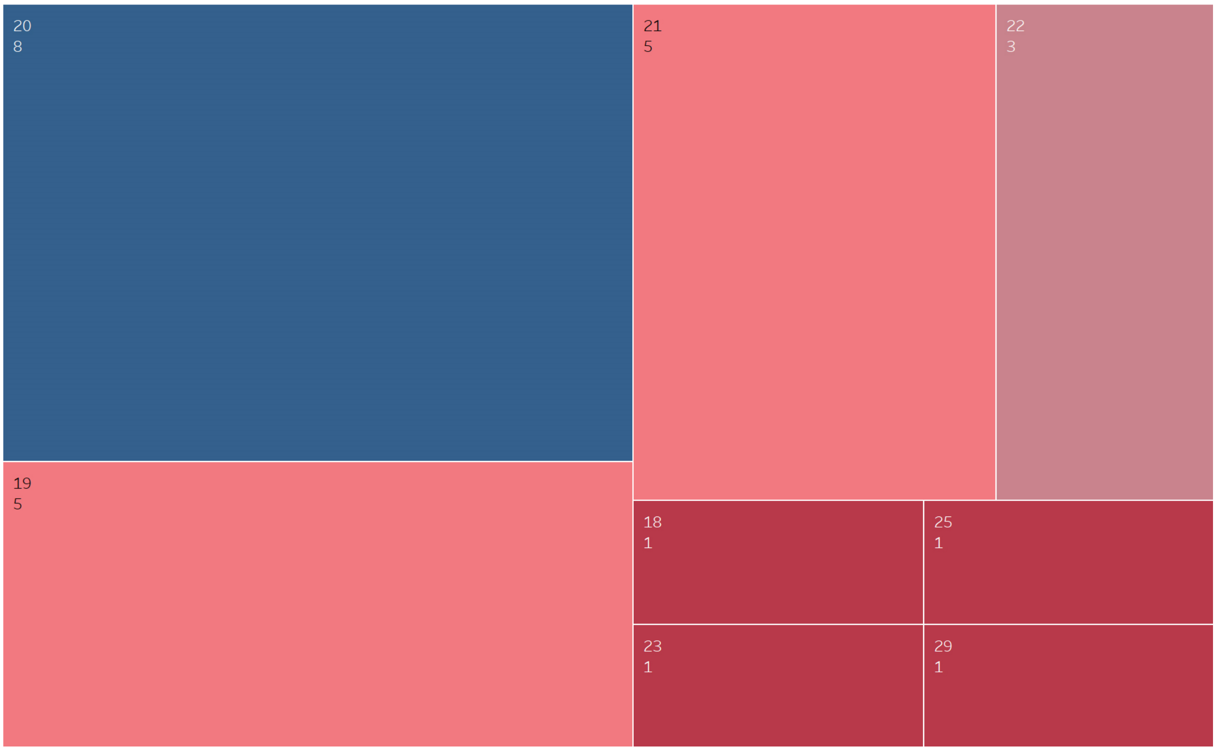


Figure 8-1 Age and count of age. Size and colour show sum of count show count of age. The marks are labelled by age and count of age.

Independently of their digital fabrication machine use, 13 participants reported having some knowledge of digital design tools while 12 reported not being familiar at all with digital design tools and software.

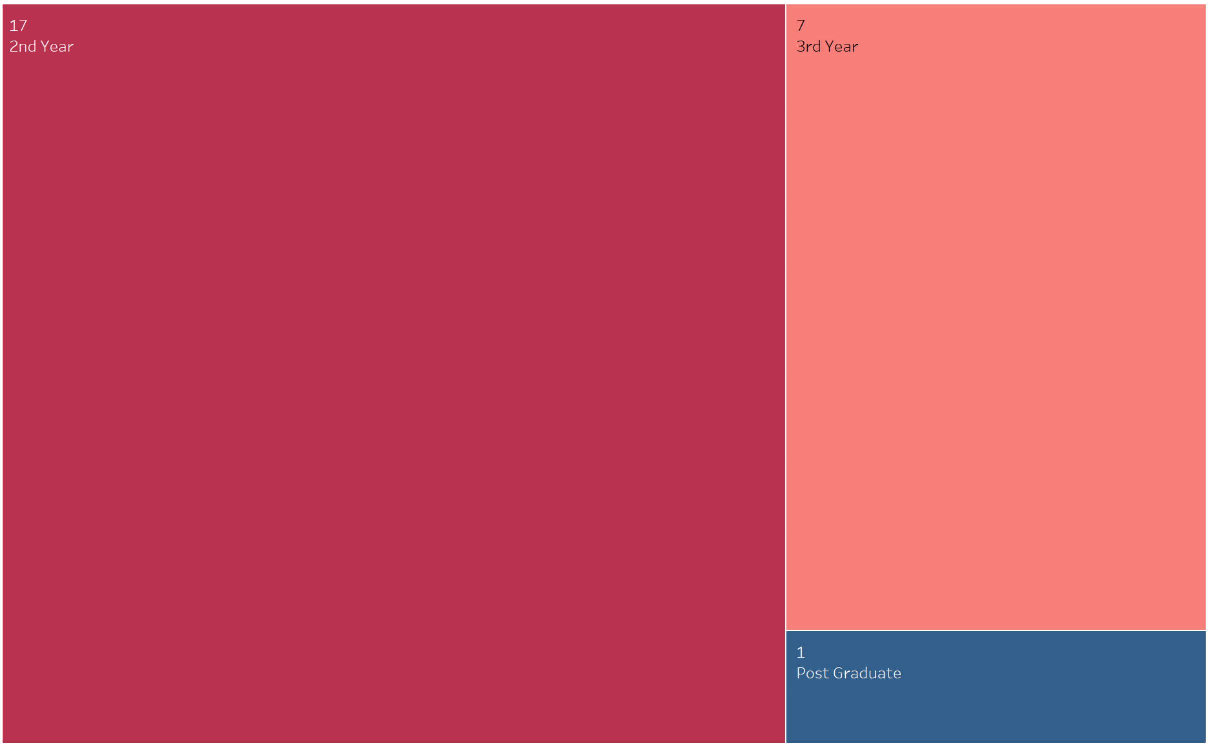


Figure 8-2 Count of year of study. Colour and size show sum of year of study. The marks are labelled by count of year of study.

Summary

Participants were coded for their age, gender, year of study, previous digital experience, previous experience of digital fabrication machines and whether they did their design or not, before starting the analysis. The number of participants is in line with other research studies in the areas of HRI and HCI which recommend the use of 15–30 participants before the law of diminishing returns begins to apply and more participants stop equating to further insights (Wright and McCarthy 2015). As the coding and analysis of the last participants was completed it was clear that no new concepts were being introduced, the central categories were well developed, saturation was achieved and the results were sufficient for this research procedure.

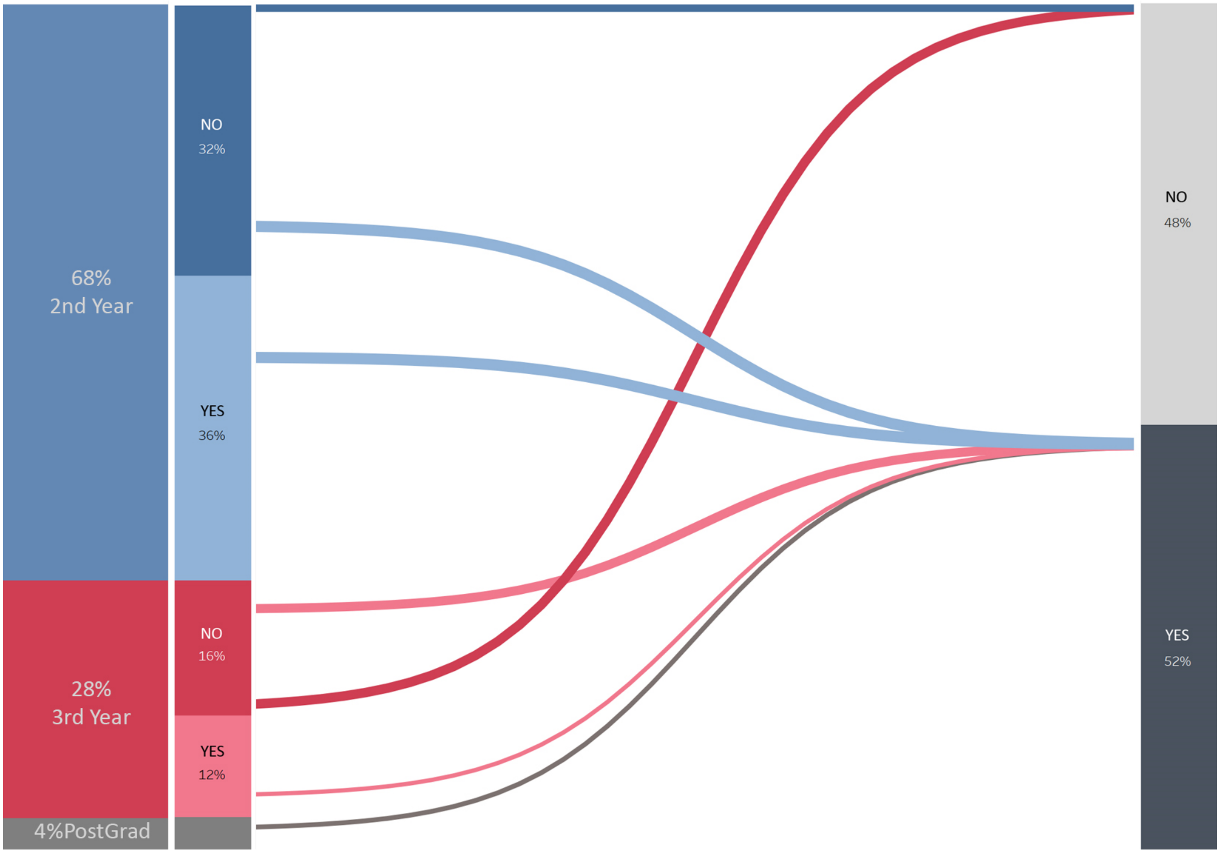


Figure 8-3 Sankey diagram showing participants divided first by year of study and second for experience with digital fabrication tools related to whereas they digitally modelled their design or not.

Design

The two training sessions and the development of the design task were treated as a single unit, considered to be ’the task’. Participants could not take part in only one of the sessions; the three of them had to be completed. Participants throughout the sessions interacted with a single, six-axis, KUKA KR60HA industrial robotic arm (section 7.5). All the participants were allowed to practise with the system and the material before starting their design task.

Materials

A cage was placed around the robot to ensure safe separation between the robot and the user when running in automatic mode. For manual mode tasks participants were in proximity to the robot. For the completion of the design task three end effectors were used: 1) a circular rotary blade; 2) a Kinect scanner; and, 3) a wooden sphere mounted at the end of the Kinect. Concrete impregnated fabric was used as the design material (section7.5.2). The phase-changing properties open a three-hour window when manipulation and collaboration could happen. A wooden frame was provided for all participants to secure the concrete cloth after cutting and during the forming process. For hydrating the cloth water bottles with a spraying nozzle were made available.

Task

Identical task conditions were provided for all participants. The aim was to design and then iteratively explore possibilities with the robot to form-find a concrete shell (Figure 8-4). Matching the physical to the digital was seen as a soft objective; participants were not required to achieve a match but to achieve a design that they felt comfortable with and following the step-by-step process described in section 7.6.3.

Measures

Data was collected via a questionnaire with 36 questions developed by the researcher (section 7.4.2). Additionally, semi-structured interviews (section 7.4.1), field notes (section 7.4.3) and videos (section 7.4.4) of the design task were also collected.   (section 7.4.1). The researcher was always present during the exercise taking notes and providing technical support to the participants.

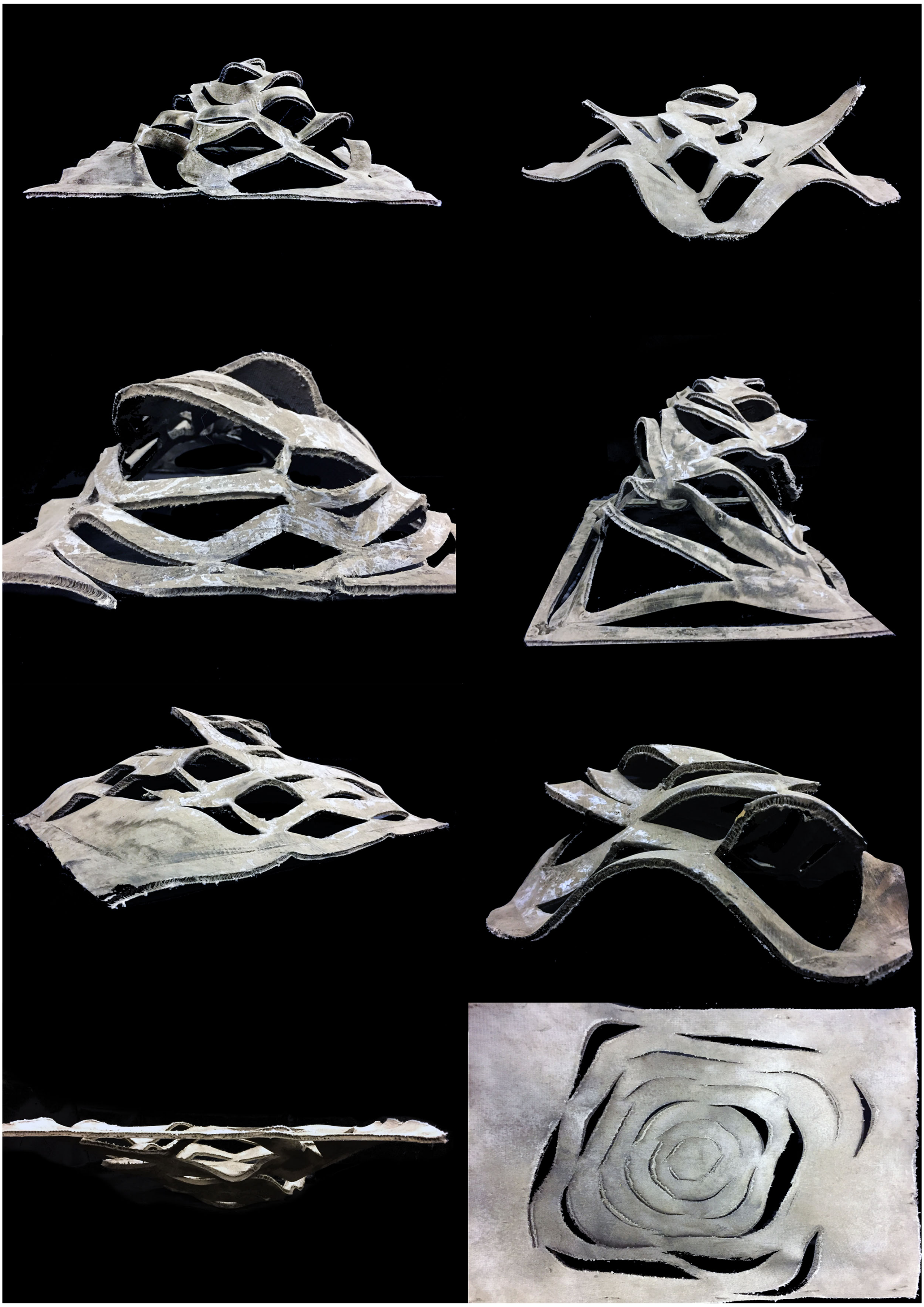


Figure 8-4 Catalogue of some of the form-found shells from the task.

Procedure

A standardised procedure was developed that was identical for all participants. Participants were individually recruited from the school of architecture. Participants were informed about their right to withdraw, the anonymity of the research procedure and their written consent obtained. Participant sessions, described in section 7.6, were scheduled around students' work and school commitments and they could attend them individually or as a group. However, data was collected individually upon completion of the design exercise.

8.2 Data Analysis

This section describes the procedure followed in the analysis of the quantitative and qualitative data using a mixed-methods research methodology.

Onwuegbuzie and Combs (2011) introduced the term 'crossover mixed analysis' to describe the ways in which analysis types associated with one tradition (e.g. quantitative analysis) can be used to analyse data traditionally associated with a different tradition (e.g. qualitative data). Furthermore, they propose nine different data analysis techniques for combining quantitative and qualitative data analysis within the same framework. These include:

1) reducing or condensing the dimensionality of qualitative data using quantitative analysis;
2) displaying visually qualitative and quantitative data together;
3) transforming quantitative data to be analysed qualitatively;
4) correlating qualitative data with quantitised data and/or vice versa;
5) consolidating multiple diverse datasets in order to create new consolidated codes;
6) comparing and examining side by side qualitative and quantitative data findings;
7) integrating qualitative and quantitative findings into a coherent whole;
8) asserting analysis to yield meta-inferences from the review of both qualitative and quantitative data; and
9) importing data to use findings from the qualitative analysis informing the quantitative analysis or vice versa (Frels and Onwuegbuzie 2013).

The data collected was analysed in two stages following a qualitative dominant crossover mixed analysis (Onwuegbuzie et al. 2012).Quantitative data was analysed as a function of participants' age, sex and year of study and a quantitative scale was established to help interpret the results from the qualitative interviews and cross-reference the findings. Braun and Clarke (2006) suggest a six-step analytical procedure: data familiarisation, generation of initial codes, searching for themes, defining and naming themes, reporting findings. These steps were followed to understand the data, although not in a linear way. The data analysis process was iterative and reflective moving back and forth across empirical data and theoretical resources. The data analysis was guided by an interest in answering the research questions of this study.

Atlas.ti, a qualitative analysis software package, was used for the coding process of the quantitative and qualitative information. The software has an approach to data analysis based on building bottom-up concepts from the data and connecting them in networks. This allows the research to follow an inductive approach in which the researcher started from observations and applying labels to the data and progressively worked upwards until patterns and regularities started to appear which allowed the development of conclusions (Friese 2014). The qualitative and quantitative data was connected through networks based on coding. Coding, in this context, means assigning categories, concepts or labels to segments of information that are relevant to the research objectives. Through the Atlas.ti networks the researcher can clearly visualise the relations between the data (Friese 2014) and relationships be visualised and understood. These networks of connections can be coded as explanatory, complementary or contradictory and can be established inside a single document or between the different pieces of information. The found networks often result in unexpected links between elements related to a theme or sub-theme.

Moreover, the software allows for quantitative data to be imported, managed and coded using a node system inside the package. The nodes corresponding to the same concept can then be linked through networks. This allows the visualisation of the negative or positive concepts that participants attribute to the collaboration and their relationship to them. For instance, a participant might have given a high score to his or her level of comfort working with the robot in the questionnaire, then during the exercise he or she could have remained at the edge of the cage without engaging with the robot; later in the interview he or she may express mixed negative and positive feelings about the robot. All of this data, including questionnaires, videos and interviews, are managed inside the software, with their codes, and linked to the participants' main node. The aim was to establish through the different links between the data sources a comprehensive view of the research exercise. This approach allows to identify patterns that define core human factors meaningful to a design scenario of HIRC and to recognise potential inconsistencies between participants' assessments of the design collaboration.

In the area of HRC discrepancies between an individual's self-report and his or her behaviour have been an issue and topic of concern for a number of decades (Natsoulas 1967; Hancock et al. 1995). Exiting research has shown that while individuals can report that they trust the robot, the statement-action relationship is not always consistent (Fong et al. 2001; Chen and Terrence 2009). Therefore, empirical research that includes both subjective and objective measurement has proved better suited to provide a more complete picture of the genesis and persistence of team fluency in human–robot teams (Hancock et al. 2011b; Hancock et al. 2011a). Additionally, each person would have differing perceptions of the intent, performance and actions of the robot and of their own design process. These perceptions when mapped onto each other may not represent the true capabilities of HIRC in design tasks. The differences in perception may be mitigated by the implementation of data analysis techniques that combine qualitative and quantitative data and allow full comprehension of the role that fluency plays in HIRC during design tasks.

8.2.1 Analysis of the Qualitative Information: Interviews

Qualitative information from the interviews, field notes and videos were analysed using template analysis (King 1998). The aim was to establish key team fluency themes, emergent themes and the relationship between them. Template analysis as a strategy to analyse qualitative data allows the researcher to establish the validity of the themes that have been identified from the literature as the most influential in the development of team fluency in a HIRC design scenario.

Template analysis will also reveal any factors particular to the design scenario and which may not be yet be acknowledged by existing research. The template and hierarchical structure for analysing the interviews will be the same as the one used for the quantitative information. During the coding and analysis of the interviews special attention was given to parameters that could indicate participants' feelings of: 1) interaction; 2) a multi-directional design process that integrates the virtual and the material; 3) a different way of design thinking enabled by the robot; and, 4) the robot contribution to the task. Additionally, consideration was given to the constructs of team fluency: trust, reliance, collegiality, robustness and improvement as described in section 4.3.

Interviews were transcribed verbatim and in full length and then analysed following the 'template analysis' guidelines as provided by (King 1998). Template analysis starts with the development of a coding template in which the major themes within the written text are hierarchically identified. The top-level codes represent the broader, big themes whereas low-level codes represent sub-themes and the lower level is represented by descriptive codes. Special care was given to code themes identified in a small number of transcripts which were assigned their own codes. The template developed by the researcher was first based on the interviews and augmented with the field notes and videos. After all qualitative information was coded the template was run through all the data to check consistency and cross-reference codes used in the interviews and in the videos and field notes. In some cases, redundant codes were removed or merged. The template was revised iteratively to ensure that it covers all the themes and sub-themes and that data is represented in the most suitable manner. Twenty-six top-level codes appeared, each with a range of between 2 to 20 low-level codes. Items with more than 20 low-level codes were revised to avoid merging many different ideas under the same topic. Similarly, top-level codes with a low number of low-level codes were cross-referenced and potentially merged with a similar one. A single participant talking about a single, unique aspect of the collaboration occurred four times. Low-level codes were divided between positive and negative feelings regarding the same action (i.e. robot contribution positive, robot contribution negative). Figure 8-4 shows an extract from the coding template. The full template used for the data analysis is presented in Appendix H.

APPEARANCE
Robot Appearance - Changes depending on the end effector
Robot Appearance - Colour – Pink

Robot Appearance - Negative - difficult to know which way it is looking
Robot Appearance - Negative - heavy
Robot Appearance - Negative - scary (Razor end effector)

Robot Appearance - positive
Robot Appearance - positive - adorable
Robot Appearance - Positive - friendly (ball end effector)
Robot Appearance - Positive - impressive
Robot Appearance - Positive - it doesn't move from the floor
Robot Appearance - positive - love talking to him

Figure 8-5 Extract of coding template, full template is in Appendix H.

Atlas.ti, was used during the development and refinement of the coding template. In Atlas.ti the free code function was used to create codes based on the concepts that are of importance to the ANT theoretical basis of this research. Coding, connecting, and visualising the data using a qualitative data analysis software package while following the principles of ANT required a specific approach. Qualitative data analysis theory and software seek to transcend descriptions of the data and provide explanations whereas the explicit intention of ANT is to provide descriptions (section 6.2).

Once all the material was coded, the search tool in Atlas.ti was used to conduct search queries and find answers that would remain hidden in the data otherwise (Friese 2014). Using a qualitative software package allows the researcher to investigate the data at various levels in a systematic and transparent way and to a higher level of accuracy than using traditional methods (Friese 2014). Additionally, the software adds rigour to the qualitative data analysis process and the coded data is available and can be queried by a third person to double check the findings (Bazeley 2013). The coding process is the most important step in the data analysis process to develop a comprehensive image of the connections between the data and the relationships that can be identified. It has to be done in a sequential and iterative way to avoid redundancy while capturing the complexity of the research exercise (Friese 2014; Wright 2015). It allows the researcher to communicate and connect with the data and facilitates the understanding of the current situation and produces a theoretically grounded map for analysis (Wright 2015).

As a final step, the text from the interviews was cleaned using the Natural Language Toolkit (NLTK) for Python in order to do feature reduction and tokenise it. The clean text was then fed into a Word2Vec neural network to find proximity and relationships between the robot, task and participants' experiences, based on their personal account of the experience.

8.2.2 Analysis of Qualitative Information: Videos and Field Notes

The fieldwork as recorded in the notebooks was focused on following the trajectories of the 'actants', both human and non-human. Following a non-anthropocentric agent requires a constant shift in the view and focus of the researcher as there is an inherent tendency to follow an individual or group of human 'actors'. Following the non-human actants that together construct the robot helped to explore and consider how the situated actions (Suchman 1987), design choices and design results were achieved.

The video material was specifically coded looking for non-verbal indicators of team fluency, such as the proximity of the participant to the robot (i.e. videos were coded for when participants remained at the edge of the cage versus moving freely around and close to the robot to compare this with their accounts of feeling comfortable or not with the robot, and find potential inconsistencies). Attributes like responsibility, trust and attribution of blame were also correlated between participants' accounts and video information (i.e. cases in which the material broke due to the robot's action and resulted in a high attribution of blame, regardless of the participant instructing the robot of the depth of the plunging vs cases were attribution of credit and blame are not related to specific robot actions).

The analysis of participants' behaviours was divided into three parts: 1) actions or what participants did; 2) decisions or changes throughout the process in which participants might or might not have acted; and, 3) events or things that happened. The coding follows this structure which allows the definition of patterns of observations and events. Additionally, after coding, participants were clustered according to common characteristics (i.e. impressed by the robot, how they reacted to the scan, actions they took, etc.) to start defining patterns of observations and events.

The team fluency construct of reliance was only evaluated from the videos and field notes as follows:

Reliance evaluates the level of engagement or reliance of the participants in the more ambiguous situations described as those in which the participant could choose to solicit input or not from the robot (e.g. after the concrete deformation). The nature of the task creates various moments where the robot has better and more accurate information than the participant over the status of the geometry in reference to the original design obtained from the simulation. This situation happens specifically after each scan and in-between plunges. The robot after scanning and comparing would have quantitative information whereas the participant would only have visual information of the deformed material but would be lacking any reference to their original design in relation to it. Additionally, when the participants are jogging the robot to push and massage the geometry, they are not aware of the amount of deformation that is happening in relation to what they originally designed.

During these moments' participants had the choice to:

1. Scan and allow the robot to further deform the geometry. In these cases, participants allowed the robot to perform the path that it suggested based on the comparison between digital and physical information. Coded as **reliance on the robot** and **reliance on the digital information.** A multiplication factor of 2 was added for participants that allowed the plunging sequence to be run in

automatic mode (i.e. sequence run fully by the robot with no direct intervention) versus those who ran the plunging sequence manually (i.e. they were holding the teach pendant while playing the program). The decision to give a higher value to those participants who ran the robot in automatic mode is because holding manually running a robot program increases the feeling of control for the human (although in both cases the robot can be stopped at any moment) and would imply less reliance on the automated process.

2. Scan and manually jog the robot for further deformations (consulting or not the digital information). Coded as **reliance on the digital information** but **not reliance on the robot**. Participants in these cases are either neglecting the robot's capabilities or deciding to explore a different direction after seeing the information provided by the robot.
3. Not scanning at all. Coded as **no reliance on the robot** and **no reliance on the digital information**. The participant in these cases renders the information provided by the robot as irrelevant. This could be due to a range of factors from lack of trust to a genuine desire to play and freely explore through the machine. The other behaviours of the participant and responses are used to define on a case by case basis.

The videos and field notes were also coded for additional indicators of the relationship between the designer and the reliability of the automated parts of the process. Robot reliability can hinder or increase human reliance on the collaboration. This was coded as follows:

Reliance on the robot:

High: Participants that allow the robot to do all the plunging and path planning by itself after scanning.

Mixed: Participants allow the robot to do the plunging based on its' own generated paths but also do some plunging by jogging the robot manually and based on their own intuition. This could be a full plunging iteration or only to fine-tune some areas.

Low: Participants that do all the plunging by manually jogging the robot themselves. Participants in this category refused to consult the robot in all instances, although knowing that it might have better information.

Reliance on the digital information:

High: Participants during the plunging were constantly consulting the digital information from the scanning and comparisons, on the screen. This includes when the participant is doing the plunging manually but keeping an eye on the screen for any changes.

Low: Participants who neglected the digital information provided by the robot and proceeded with the plunging, manually jogging the robot based on his or her intuition.

Reliance factor:

- **Scale from 0 to 5** based on participants' actions. The numbers refer to the amount of scan and comparison iterations that the participant performed. The comparison may have resulted in a further pushing iteration or in the participant deciding to leave the shape to settle.

Each situation was specifically coded to indicate participants' actions. Participants could also have a combination of different degrees of reliance as they would react differently to each scan (i.e. they would go for a fully automated plunging sequence based on the robot-generated paths after the first scan and do manual jogging after the second scan). This as part of the exploratory design process or as a response to the robot's and material's actions (i.e. participants decide after the first plunging iteration that they are interested in exploring a different emergent behaviour or geometry and deviate from their initial design, and the robot's information is then irrelevant).

A special coding indicator was developed for cases in which participants allowed the robot to generate its paths and plunge the material accordingly only to be surprised at the end by the matching of digital and physical geometries (i.e. this could be considered an indicator of not understanding the attributes and capabilities of the robot or not trusting in them).

The scanning could be performed after hanging the shell before starting any deformation, and after each plunging iteration. The comparisons could be done between the digital form-found shape and the physical shape or between the different deformation stages after pushing. The first case is meant to allow the physical and the digital to match whereas the second is to understand how the material is deforming independently of the original digital shape. There was not any limit on the number of times that participants could ask the robot for information during the task. The number of pushing and scanning iterations was solely decided by the participant and there was not a time limit for the completion of the task.

8.2.3 Analysis of Quantitative Information: Questionnaires

A Likert scale questionnaire was designed and applied to all the participants after finishing the design exercise to rate agreement with the notions of team fluency. The set of fluency notions that was evaluated through the questionnaire has been researched from the literature and adapted to the human−industrial robot collaborative design scenario as described in section 5.6. It is important to note that currently there are no accepted measures, practises or methods to evaluate fluency in HRC (Hoffman 2019) and the accepted ones rarely refer to the cases when the robot is a robotic arm (Charalambous 2014). Additionally, there are no metrics for design or intellectual creative joint tasks.

In order to assess how fluent participants, perceive the collaboration to be in a subjective, measurable way, questionnaires included single statements and composites of indicators related to the same measure. The questionnaire consisted of 36 questions and was divided into two parts.

Two Likert scales were used for each section of the questionnaire. Aspects of HIRC trust in the literature are measured on a five-point Likert scale whereas other aspects of HRC have been traditionally measured using seven-point Likert scales. Larger scale Likert scales provide the benefits of offering more variance, a higher degree of measurement precision and provide a better opportunity to detect changes as well as give the participants more power to explain a point of view. However larger scales might take participants a longer time to complete and may discourage them with the amount of decisions they have to take. On the one hand it can be argued that they offer a better understanding and a 5 in a five-point scale may score 9 or 10 in a ten-point scale; while this can be seen as an advantage of having a wider scale it might also mean that the differences between scores 9 and 10 are irrelevant (Wittink and Bayer 2003). A decision to keep two scales was made in order to keep with the existing measures from the literature and be able to compare the results with previous research in HRC.

To avoid confusion in the participants due to the different scales, the five-point one had answers in written format (i.e. highly concerned to highly unconcerned) whereas for the seven-point scale the answers were numerals from 1 to 7 with 1 indicating not at all agreement with the notion and 7 indicating full agreement. To keep consistency and avoid errors by the participants the most negative feeling or disagreement was to the outer left in both questionnaires, increasing positively to the right. The outer right measure was the most positive reflecting higher levels of agreement, trust, comfort, etc.

The two parts were divided as follows:
The first part, consisting of 20 questions, was dissected and adapted to the design scenario from a psychometric scale that measures trust in HRC developed by George Charalambous and with a specific focus towards evaluating the aspects of trust in the robot, in the human and in the HRT (Charalambous et al. 2016). Questions regarding robot and material feedback were developed and incorporated as the original scale does not consider any feedback from the robot, nor the material. Response to the items was assessed using a five-point Likert scale from 1 (strong disagreement with the evaluated parameter) to 5 (strong agreement with the evaluated parameter). Scores were summed to give a single number representing subjective

trust ranging from 20 to 100.

The second part, consisted of 16 additional questions. These had a specific focus to evaluate the robustness, collegiality and improvement of the HRT. The answers consider aspects such as the robot's teammate traits, responsibility, robot's contribution, attribution of credit, attribution of blame, improvement and partnership, which together comprise the measurements for the robustness, collegiality and improvement themes. Questions were aimed to evaluate the reaction of the human 'teammate' to the robot. A total of 15 questions asked the participants to rank agreement with a sentence on a seven-point Likert scale from "not at all" (1) to "fully" (7) agree. The last question, asking the participants to name the robot, had an open-ended response. The question had a score of 1 for a female name, 7 for a male name and 4 for neutral names (i.e. animals, cartoon characters, objects).

The scores of the second part of the questionnaire were summed to give a single number for each of the three themes, according to the number of questions defining its sub-themes: Collegiality has seven questions with a total score ranging from 7 to 49(Figure 8-5);

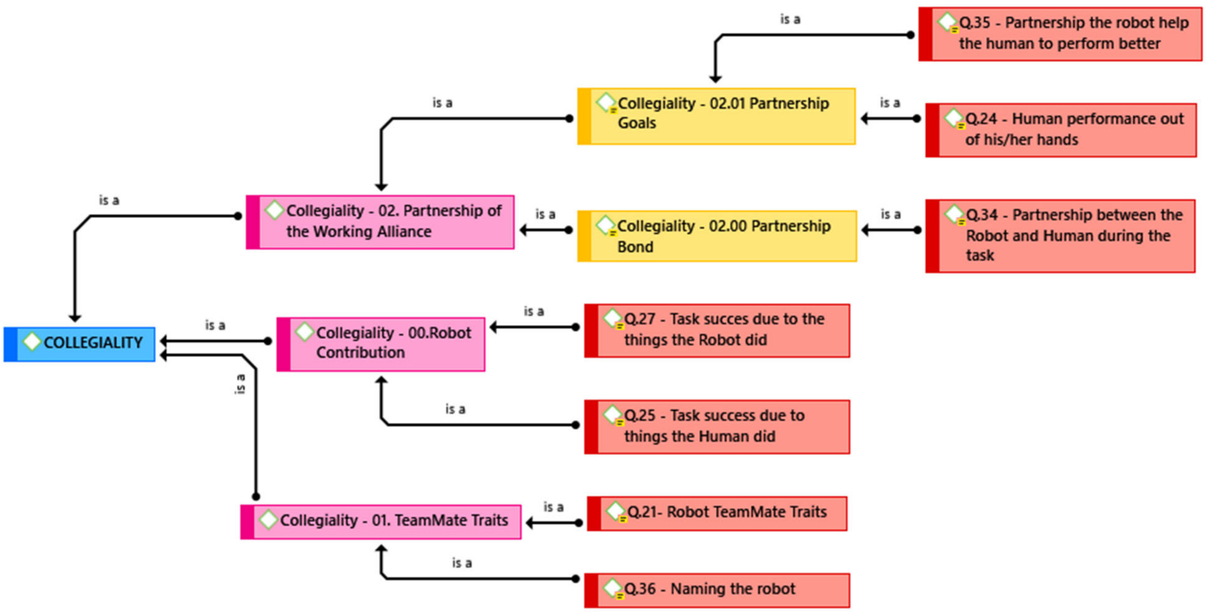


Figure 8-6 Collegiality question indicators per each sub-theme.

Improvement three questions and a range of scores from 3 to 21 (Figure 8-6);

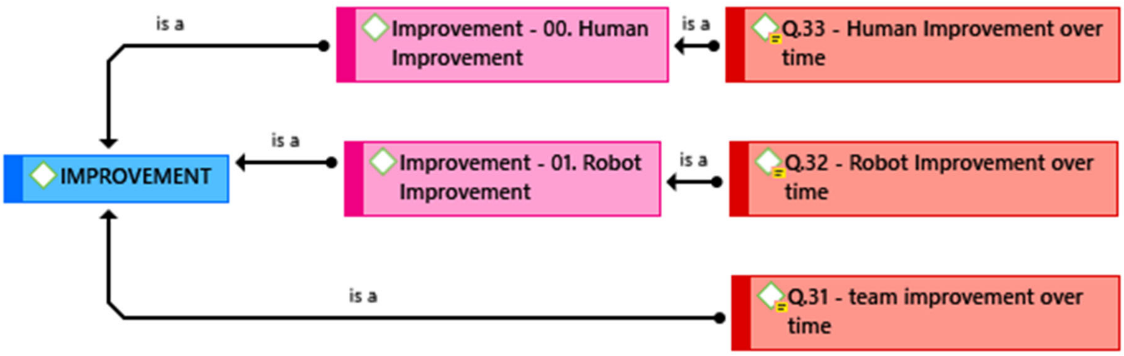


Figure 8-7 Improvement question indicators per each sub-theme.

and robustness six questions and scores ranging from 6 to 42.

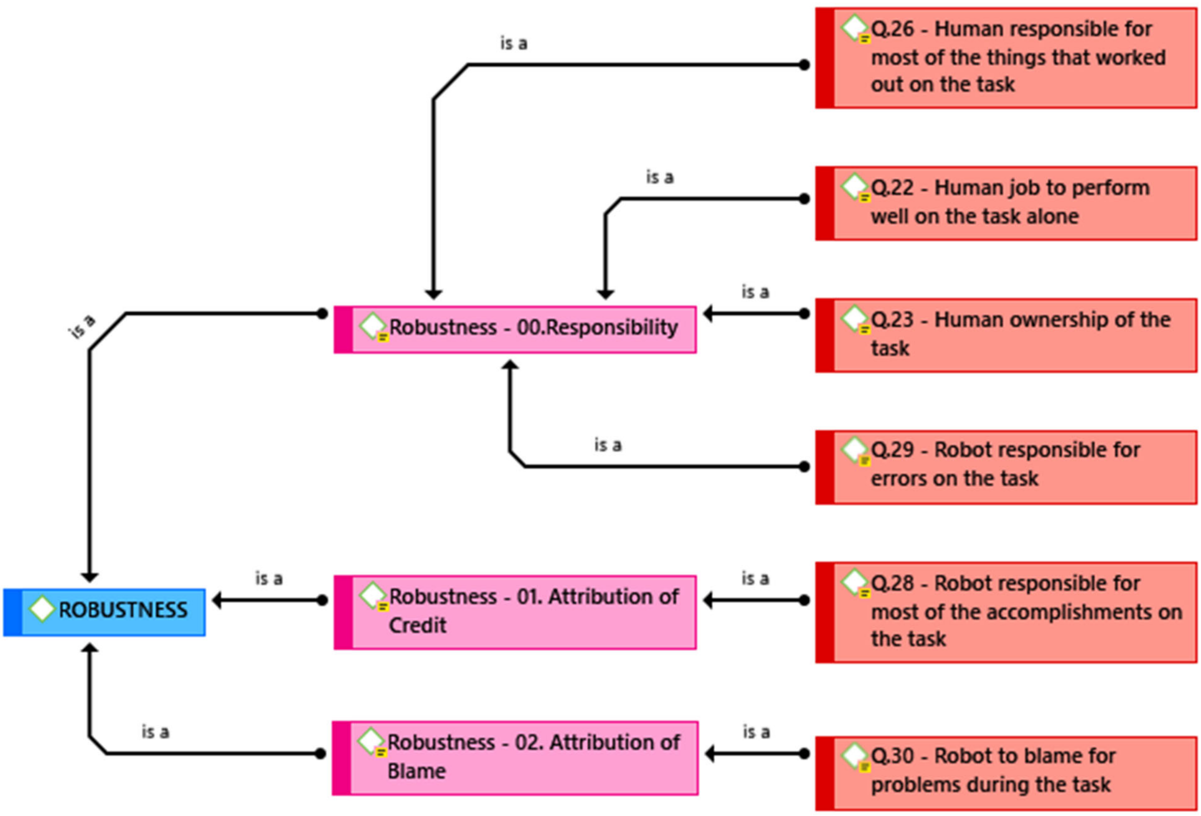


Figure 8-8 Robustness question indicators per each sub-theme.

All the themes – independently of the number of items – were complemented by the additional qualitative information. Single measures were not used on their own to make inferences at any stage nor data analysis conducted on a theme using individual items (Gliem, Joseph; Gliem 2003).

The two Likert scales were finally transformed to the higher seven-point scale. The higher scale was selected to reduce the information loss. Matching questionnaires to the lower Likert scale results in information losses as details are lost (Wittink and Bayer 2003; Norman 2010b; Frels and Onwuegbuzie 2013).

The transformation formula was applied based on the minimum of both scales which is one and using the common statistical package for the social sciences (SPSS) formula

$$Y = (B - A) * \frac{x - a}{b - a} + A$$

Equation 8-1 Likert-scale transformation formulae.

Since the minimum of the five-point scale is 1, then a = 1, b = 5 in the first transformation.
For the second transformation, A = 1, B = 7. Putting them together gets:

(7 - 1) * (x - 1) / (5 - 1) + 1

The results after matching both scales are:

Table 8-1 Likert-scale transformation

x 1	x 2
1	1.0
2	2.5
3	4.0
4	5.5
5	7.0

After transforming both scales into a common seven-point scale, scores from all the questions were summed to give a single number representing team fluency ranging from 36 to 252.

8.2.3.1 Reliability analysis

The internal consistency and reliability of a test are important measures. Cronbach's alpha refers to the internal consistency of items in the scale and is the most used formula for testing questionnaires using a Likert scale (Kline 2005). Cronbach's alpha is measured from 0 to 1 and it generally increases when the correlations between the items increase. The closer the Cronbach's alpha coefficient is to 1 the greater the internal consistency of the items in the scale. A generally accepted rule is that an alpha above 0.7 indicates acceptable reliability with 0.8 or higher being considered as appropriate reliability (Kline 2000; Kulić and Croft 2007). Values higher than 0.95 are not desirable as they may indicate that the items are entirely redundant. Researchers suggest that when measuring psychological constructs values below 0.8 can also be acceptable (Kline 2000). Additionally, even when cut-off values have been suggested these are only guidelines and need to be interpreted with care; Cronbach's alpha depends on the number of items. If the number of items increase Cronbach's alpha will also increase without any increase in internal consistency nor in reliability. The Cronbach's alpha equation, shown below, indicates how Cronbach's alpha is proportional to the number of items squared (N^2).

$$Cronbach\ alpha\ (\propto) = \frac{N^2(\overline{Cov})}{(\sum s^2)\ (item) +\ \sum Cov(item)}$$

Equation 8-2 The Cronbach alpha formulae.

Trust Questionnaire

Cronbach's alpha for the trust questionnaire assessed responses using a five-point Likert scale from 1 (strongly disagree/unreliable/unsafe, etc.) to 5 (strongly agree/reliable/safe, etc.) before transforming it into the higher seven-point scale. Scores from questions worded in a negative direction were subtracted from 6 (maximum scale +1). This step is necessary before performing reliability data analysis. If the negative-worded items are not reversed Cronbach's alpha will be negative, which is not useful.

Data was reversed, prepared and entered into SPSS where a reliability analysis was performed.

The reliability and scale statistics are shown in the following table.

Table 8-2 Reliability and scale statistics of the non-transformed trust questionnaire

Cronbach's Alpha	SD	Mean	Variance	Sample Size	Number of items
0.73	6.05	75.24	36.61	25	20

Transformed Trust Questionnaire

The questionnaire was then transformed into the higher seven-point scale and tested for reliability during the scale change. There were no significant changes to the reliability statistics after the scale transformation (Table 8-3). The seven-point Likert scale was then deemed suitable and adopted for the evaluation of team fluency.

Table 8-3 Reliability and scale statistics of the transformed trust questionnaire

Cronbach's Alpha	SD	Mean	Variance	Sample Size	Number of items
0.76	9.41	102.06	88.72	25	20

Collegiality, Improvement and Robustness Questionnaire

Cronbach's alpha for the second part of the questionnaire measuring the collegiality, improvement and robustness constructs was also calculated (Table 8-4)

Table 8-4 Reliability and scale statistics of the second part of the questionnaire

Cronbach's Alpha	SD	Mean	Variance	Sample Size	Number of items
0.80	12.95	76.08	167.74	25	16

The analysis of the data showed reliability and consistency in the responses obtained from both parts of the questionnaire. Therefore, the data was merged into a single dataset containing all the measures composing team fluency.

Team Fluency Questionnaire

The next steps were to measure the reliability and internal consistency for all the items in the team fluency construct (Table 8-5) and to identify their relevance and contribution towards the overall team fluency.

Table 8-5 Reliability and scale statistics for the team fluency questionnaire

Cronbach's Alpha	SD	Mean	Variance	Sample Size	Number of items
0.83	18.45	178.94	341.42	25	36

The literature suggests 0.7 as the generally accepted cut-off for Cronbach's alpha; however, it also suggests that lower values are acceptable when measuring psychological constructs (Kline 2000). Furthermore, the team fluency scale is a newly developed scale based on ample review of previous isolated HRC measuring scales for trust and fluency. The ones related to fluency are not specific to robot arms but adapted to it. It also includes additional items specific to the design task and the material feedback, non-present in other scales that have been specifically designed and added.

Standard deviation shows how much variation is likely to exist between a single value in the data set and the mean. A low standard deviation suggest values are close to the mean whereas a high standard deviation suggests that values are spread out and further from the mean. The mean and standard deviation for each item of the questionnaire were calculated to understand in which items participant ratings differ most. Table (8-6) below illustrates the mean and standard deviation for each item of the team fluency questionnaire.

Table 8-6 Mean and standard deviation for each team fluency item

Item Number	Mean	SD
Q. 1	5.7	0.1
Q. 2	5.7	1.2
Q. 3	5.6	1.0
Q. 4	6.1	1.1
Q. 5	5.4	1.3
Q. 6 (R)	5.4	0.9
Q. 7	5.1	1.0
Q. 8	5.7	1.0
Q. 9	5.6	0.7
Q. 10	5.1	1.4
Q. 11 (R)	4.9	1.4
Q. 12	6.3	1.2
Q. 13	6.0	0.9
Q. 14	5.5	0.6
Q. 15	5.3	1.2
Q. 16	5.3	1.1
Q. 17	3.8	1.3
Q. 18	4.0	1.4
Q. 19	5.6	1.0
Q. 20	5.5	1.4
Q. 21	4.1	1.6
Q. 22	4.6	1.7
Q. 23	4.8	1.5
Q. 24	4.9	1.6
Q. 25	3.7	1.6
Q. 26	3.8	1.6
Q. 27	4.5	1.4
Q. 28	4.2	1.6
Q. 29	5.0	1.8
Q. 30	5.5	1.6
Q. 31	5.2	1.4
Q. 32	4.0	1.6
Q. 33	5.4	1.4
Q. 34	5.6	1.4
Q. 35	5.9	1.4
Q. 36	4.8	2.4

Note: The (R) represents items negatively worded which have been reversed.

The mean and standard deviation for each item under team fluency indicate that the participants’ ratings do not vary greatly. The highest score appears on item number 12 related to participants feeling comfortable that the robot would not hurt them. The lowest score is on item 25 which is related to the attribution of credit for the success of the task mainly to the human: *“the success of the task is largely due to the things I did”*. This suggests that participants attribute credit on the success of the task to the robot partner. The standard deviation is higher on the last question which was an open question and related to naming the robot. It was scored based on whether the name given was male, female or neutral, which included animals and cartoon characters; the rationale behind this construct is explained in section 5.6.1.

The total fluency score for each participant was obtained by adding the ratings recorded from each participant for each item. Team fluency had a scoring range from 36 to 252.The maximum team fluency rate was 213 while the minimum 151.5 and the average recorded team fluency score was 180 (SD = 15.09). This is another indicator that participants’ ratings generally conform. The full table with the participants’ ratings for each item of the questionnaire along with the mean and standard deviation are included in Appendix J.

Finally, the item-total statistics were analysed (Table 8-7). These are an important output from SPSS as they present which items contribute more to the overall reliability of the test and are more representative of team fluency. They also indicate items that are not contributing to the reliability and that could be removed. The item-total statistic from SPSS includes five columns; however, only the columns ‘correct item-total correlation’ and ‘Cronbach’s alpha if item deleted’ have been retained for the purpose of this analysis.

Table 8-7 Item-total statistics

Item Number	Correct Item-total Correlation	Cronbach's Alpha if Deleted
Q. 1	0.61	0.82
Q. 2	0.49	0.82
Q. 3	0.36	0.82
Q. 4	0.26	0.82
Q. 5	0.22	0.83
Q. 6	0.07	0.83
Q. 7	0.02	0.83
Q. 8	0.25	0.82
Q. 9	0.35	0.82
Q. 10	0.18	0.83
Q. 11	0.06	0.83
Q. 12	0.31	0.82
Q. 13	0.49	0.82
Q. 14	0.21	0.83
Q. 15	0.10	0.83
Q. 16	0.53	0.82
Q. 17	0.00	0.83
Q. 18	0.17	0.83
Q. 19	0.31	0.82
Q. 20	0.33	0.82
Q. 21	0.05	0.83
Q. 22	0.33	0.82
Q. 23	0.21	0.83
Q. 24	0.55	0.81
Q. 25	0.42	0.82
Q. 26	0.38	0.82
Q. 27	0.55	0.81
Q. 28	0.70	0.81
Q. 29	0.25	0.83
Q. 30	0.27	0.82
Q. 31	0.36	0.82
Q. 32	0.06	0.83
Q. 33	0.48	0.82
Q. 34	0.67	0.81
Q. 35	0.67	0.81
Q. 36	0.34	0.82

Reliability analysis for team fluency yielded a Cronbach's alpha of 0.83 which is within the accepted recommendations from the literature. The suggested minimum cut-off value is between 0.7 and 0.8 (Kline 2000; Bartneck et al. 2009a).

Eliminating the items that are not contributing to overall reliability is a step towards improving the scale and understanding what factors are more relevant to evaluating team fluency in a human–robot design scenario. The third column in the item-total statistics indicates how much the Cronbach's alpha will change upon removal of any of the items. These are items that do not relate to the scale and may be better if removed. Additionally, by deleting them the Cronbach's alpha scale changes by a significant amount. Items 34, 35, 28, 27 and 24 are the ones that represent the greater variations. If removed the Cronbach's alpha will lower to 0.81. Thus, removing them would not change Cronbach's alpha by a significant margin. None of the items if individually removed yields an increase to Cronbach's alpha.

A different test to remove specific items on a scale is the 'correct item-total correlation'. This variable indicates the relation between the overall score of the test and the score of the item after excluding the item in question from the total score. If this last correction is not performed inflation of the item-total correlation may happen (Kline 2005). Loewenthal (1996) suggests a range between 0.15 and 0.3 for item removal. Applying this rule by taking the generally accepted item-total correlation of 0.2 results in items 6, 7, 10, 11, 15, 17, 18, 21, and 32 being removed. The table below (8-8) shows the removed items and their item-total correlation score.

Table 8-8 Removed items from the team fluency scale

Item number	Item	Correct Item-total Correlation
6	I knew the scanning information from the robot would be (highly accurate – highly inaccurate)	0.07
7	The information from the scanning was useful for my downstream design decisions (very helpful – very unhelpful)	0.02
10	The size of the robot was (highly intimidating – highly encouraging)	0.18
11	The robot cutting and pushing tools seemed (highly unreliable – highly reliable)	0.06
15	If I had more experiences with other robots I would feel about this task (highly concerned – highly unconcerned)	0.10
17	If the task was more complicated and I had to work with the robot I might have felt (highly concerned – highly unconcerned)	0.00
18	I might not have been able to work with the robot had the task been more complex (strongly agree – strongly disagree)	0.17
21	To what extent does the robot has the characteristics that you would expect from a human partner doing the same tasks?	0.05
32	The performance of the robot in this task improved over time	0.06

After removing these nine items, the reliability analysis is run again on the remaining 27 items. The new statistics for the revised scale are shown in the Table (8-9) below.

Table 8-9 Reliability and scale statistics of the remaining 27 team fluency items

Cronbach's Alpha	SD	Mean	Variance	Sample Size	Number of items
0.85	17.00	141.86	289.28	25	27

The Cronbach's alpha has now increased to 0.85 suggesting that the revised team fluency scale of 27 items has increased its reliability.

The analysis has ensured the reliability of the quantitative data collected to evaluate team fluency in design HIRC. It has also enabled the detection and removal of the weaker items and increased the reliability of the scale. The next step is to analyse the measures and composite measures as they were designed to evaluate the different constructs of team fluency.

8.2.3.2 Multiple factors

This section presents a review of the measures that have been used to evaluate the different underlying constructs that comprise team fluency as outlined in the theoretical framework in section 4.3. These constructs are based on research in the literature and are presented as a basis to discuss the research findings and the future of team fluency in human−robot collaborative design settings. The composite measures have been reduced to their significative items based on the previous reliability analysis

Each construct includes all the downstream measures for each theme. Although all the measures are currently phrased to evaluate the participant's perception of team fluency, they can be adjusted for an observer scenario (Hoffman 2013b; Hoffman 2013a). The Cronbach's alpha is reported for each measure to represent its internal consistency.

1) Trust in the robot elements: This composite downstream measure evaluates the trust that the robot evokes in the human; it includes the physical and digital aspects of the robot (i.e. the information that it is conveying). It consists of the following indicators and items:

- Perceived robot and end effector reliability

"I felt the robot was going to do what it was supposed to do"
(very unreliably – very reliably).
"The scanning, cutting and pushing seemed like they could be"
(highly reliable – highly unreliable).

- Perceived robot motion

"The way the robot moved made me feel"

(highly uncomfortable – highly comfortable).

"The speed at which the robot performed its tasks made me feel"

(highly uncomfortable – highly comfortable).

"The robot moving in the expected way was"

(strongly concerning – strongly non-concerning).

- Perceived reliability of the information it is conveying to the design task

"I felt the information given by the robot was"

(very useful – very useless).

Cronbach's alpha for this measure was found to be 0.643. Although this figure is below the accepted cut-off value of 0.7, lower values, in the literature, are generally accepted when measuring psychological constructs (Kline 2000).

2) Trust in the human elements: This composite measure evaluates the trust that the human feels in the robot due to his or her own performance, previous experience and expertise. It consists of the following indicator items:

- Perceived human performance

"By looking at the deformation of the material I could decide my next move"

(strongly disagree – strongly agree).

"I believe the robot likes me"

(strongly disagree – strongly agree).

- Perceived human safety

"I felt while interacting with the robot"

(very unsafe – very safe).

"I was comfortable the robot would not hurt me"

(strongly disagree – strongly agree).

"I trusted that to cooperate with the robot was"

(very unsafe – very safe).

Cronbach's alpha for this measure was found to be 0.767.

3) Trust in the external elements: This composited downstream measure evaluates the trust that the human perceives due to the characteristics of the task. It consists of the following indicator items:

- Perceived task complexity

"The complexity of the task made working with the robot"

(very uncomfortable – very comfortable).

- Perceived interaction with the robot

"The task made interaction with the robot"

(very easy – very complex) (reversed scored).

Cronbach's alpha for this measure was found to be 0.753.

4) Collegiality: This composite downstream measure evaluates the robot's perceived character traits related to it being a team member and consists of the following indicator items:

- Robot contribution

"The success of the task was largely due to the things I did"

(reverse scored).

"Our success was largely due to the things the robot did."

- Partnership: This downstream measure has been taken from the adaptation that Hoffman (2013a)did from the 'Working Alliance Index'. It consists of the 'bond' and the 'goal' sub-scales:

- The bond sub-scale consists of the following indicator:
  "The robot was a partner for me in this task."

- The goal sub-scale consists of the following indicators:
  "To what extent did you feel that your performance on this task was out of your hands?"
  "The robot helped me perform better on this task."

- The complete measure additionally includes the following individual, open question:
  "How will you call the robot? (suggest a name)."

Cronbach's alpha for this measure was found to be 0.764.

5) Improvement: This composite downstream measure evaluates the perceived improvement understood as the team members' adaptation to each other. Learning can be considered one way to adapt (Terveen 1995). In this case the robot is not learning nor adapting so the measure is taken in relation to the human. It consists of two independent indicators and one individual question:

- Human Improvement

"My performance in this task improved over time"

- Robot Improvement

"The performance of the robot in this task improved over time"

- The complete measure additionally includes:

"The robot and I improved our performance on this task over time."

Cronbach's alpha for this measure was found to be 0.901.

***6) Robustness**:* This composite downstream measure evaluates the functionality of the team, as opposite to its dysfunction. It consists of the following indicator items:

- Responsibility

"To what extent did you feel it was only your job to perform well on the task?" (reverse scored).

"To what extent did you feel ownership of the task?"

- Attribution of credit

"I am responsible for most things that we did well on the task" (reverse scored).

"The robot should get credit for most of what is accomplished on this task."

"The success of the task was largely due to the things I did" (reverse scored).

"Our success was largely due to the things the robot did."

- Attribution of blame

"I hold the robot responsible for any errors that were made on this task."

"The robot is to blame for most of the problems that we encountered in accomplishing this task" (reverse scored).

Cronbach's alpha for this measure was found to be 0.711.

The indicators that were not successful for the measure of team fluency in a design HIRC scenario have been indicated in Table (8-8). It would be worth examining them with different task conditions before eliminating them from the analysis of team fluency in HIRC design tasks.

8.2.3.3 Analysis of variance

The year of study of the participants became a variable of interest for further consideration during the development of the design exercise. It appeared that participants need a level of maturity in their design thinking before they can start to accept other agencies, such as the robot and the material, in it. This hypothesis was made after observing that participants from earlier years were more inclined to play with the robot and use it for plunging by jogging it manually. In these cases, the target shape was based on their intuition or personal conceptualisation of the task and defined by their jogging of the robot. However, more mature participants, from higher years, seemed to be interested in developing a more systematic way of thinking and incorporating parametric design methods into their process. During the design exercise it appeared that they consider the input from the robot at each iteration. They would also reflect on it as valuable information to understand quantitatively the material process and how the design was evolving in respect to their initial intentions. From an observer′s point of view, participants in higher years would be more inclined to follow the plunging pattern suggested by the machine.

In the context of this research study, it became interesting to investigate whether there was a statistically significant difference in the perceptions of team fluency between the responses obtained from second year and third year participants and to understand how the variable of year or study, understood as maturity in their design thinking, impact the designer evaluation of team fluency.

An ANOVA analysis of variance was used to determine whether the group means are statistically significantly different. ANOVA is a parametric test based on six assumptions. The first three are related to the design of the study and include having:

1. One independent variable measured at a continuous level.
2. Two independent variables where each one consists of two or more independent groups.
3. Independence of observations, meaning the groups are independent and participants in one group are not part of the other.

The second three are related to how the data is fit for the test and involve the following:

1. There are no significant outliers.

2. Data is approximately normally distributed.

3. Variance should be equal (homogeneity of variance).

Therefore, before carrying out the ANOVA test, a boxplot inspection for outliers, a test of normality and a test of homogeneity were carried out to ensure that all the assumptions are met. Data was entered into SPSS to carry out the three tests.

Boxplot Test for Outliers

Boxplots are a graphical representation that allow the researcher to visually inspect that the data is normally distributed. The boxplot test from SPSS was used. It was found that there were no outliers in the data, as assessed by visual inspection of a boxplot for values greater than 1.5 box-lengths from the edge of the box (Figure 8-8).

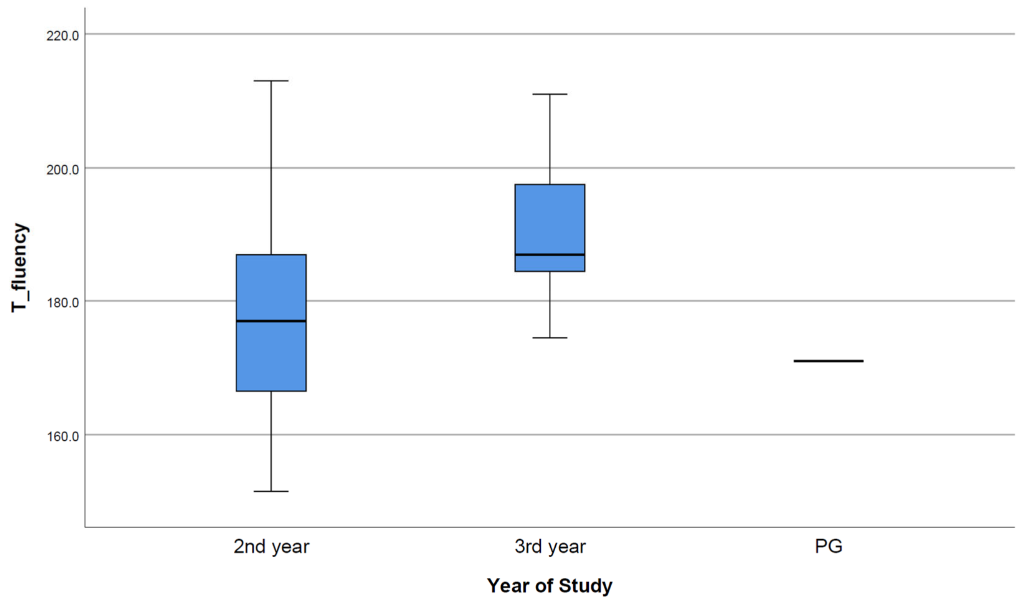


Figure 8-9 Assessment of outliers by boxplot visualisation.

Saphiro-Wilk test for Normality

The Saphiro-Wilk test for normality was used as it is normally recommended for small sample sizes (< 50 participants) (Maxwell and Delaney 2004). It investigates if the collected scores deviate from a normal distribution. The test will compare the scores against a normally distributed set of scores with the same mean and standard deviation. If the data is normally distributed it would not be significantly different from a normal distribution with a significance level higher than 0.05 ($p > 0.05$). If the data is not normally distributed, the assumption of normality is violated and the significance level will be less than 0.05 ($p < 0.05$). The results are presented in Table (8-10).

Table 8-10 Saphiro-Wilk test for year of study

		Saphiro - Wilk	
Year of Study	Statistic	df	Sig
2nd Year	0.98	17	0.92
3rd Year	0.96	7	0.83

Team fluency was normally distributed for the second year and third year students, as assessed by Saphiro-Wilk's test ($p > 0.05$). The Saphiro -Wilk test scores obtained for team fluency for the second year are Sig = 0.92, $p > 0.05$ and for third year are Sig = 0.83, $p > 0.05$.

Homogeneity of Variance

A Levene test was used to test the homogeneity of variances. The Levene test for equality of variances tests the hypothesis that the population variances are equal, meaning that group samples are drawn from populations with the same variance. A statistically significant result ($p < 0.05$) indicates that population variances are not equal and you have violated the assumption of homogeneity. On the other hand, if Levene's test is not statistically significant ($p > 0.05$) variances are equal and the assumption of homogeneity of variances is met. The output is shown in Table (8-11).

Table 8-11 Homogeneity of variance test across years of study

Levene Statistic	df1	df2	Sig
0.45	1	22	0.50

For the team fluency scores obtained between the different years of study there was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = 0.50$).

Summary

The collected data for evaluating team fluency meets the three assumptions for parametric analysis. There were no outliers, as assessed by boxplot; data was normally distributed for each group, as assessed by Saphiro-Wilk test (p > 0.05); and there was homogeneity of variances, as assessed by Levene's test of homogeneity of variances (p = 0.50). Therefore, parametric statistical analysis tools like one-way or two-way analysis of variance can be used to perform statistical analysis on the data.

One-way ANOVA

A one-way analysis of variance was carried out between the years of study to explore any difference between design maturity and perception of team fluency in the data obtained from the exercise. The results are presented in Table (8-12).

Table 8-12 Descriptive statistics for the data across the year of study

Year of Study	Mean	SD
2nd Year	177.5	16.0
3rd Year	191.0	12.0

Participants in the third year experienced a higher level of team fluency (M = 191.0, SD = 12.0) when compared to participants in their second year (M=177.5, SD = 16.0). An ANOVA is statistically significant when not all the group means are equal in the population (p < 0.05). Alternatively, when p > 0.05 there are no statistically significant differences between the group means. The results of the one-way ANOVA are shown in Table (8-13).

Table 8-13 One-way ANOVA output

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	890.2	1	890.20	4.0	.06
Within Groups	4945.5	22	224.8		
Total	5835.7	23			

The perception of team fluency was statistically different between participants in different years of study, $F (1, 22) = 4.0$, $P = 0.06$.

The one-way ANOVA analysis of variance indicates statistically significant difference between the responses to team fluency obtained from the participants in the different years of study. Participants were in their second year or third year of architectural education. Figure (8-9) represents the output of the one-way ANOVA in a bar chart with confidence intervals. The next step taken was to carry out a second analysis of variance to determine if the gender combined with year of study has an impact on the perception of team fluency.

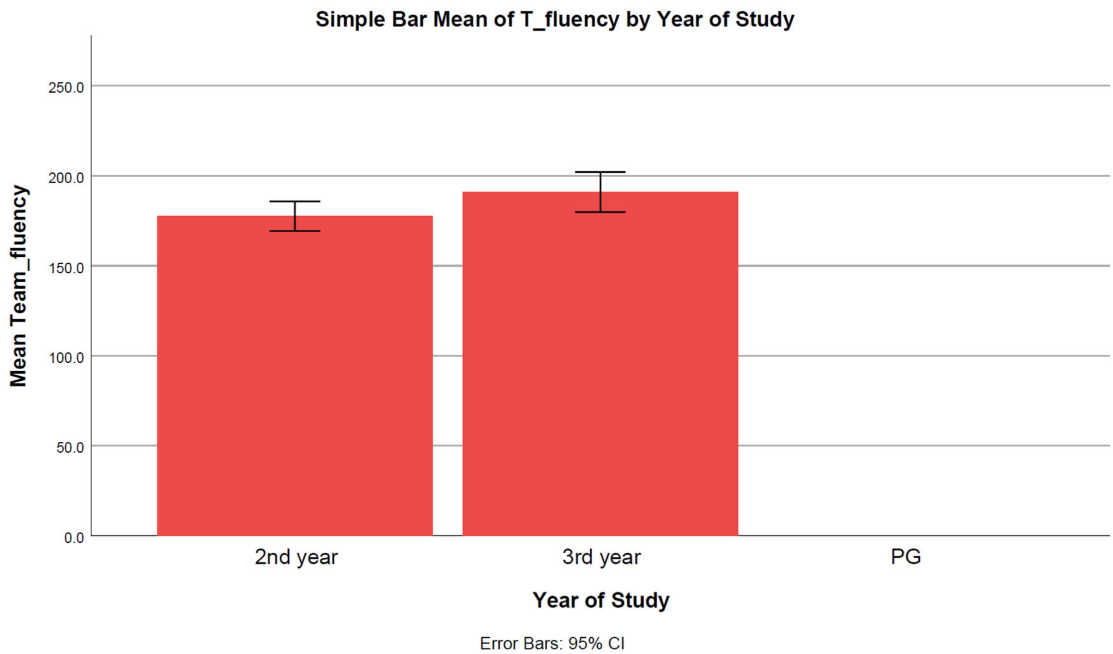


Figure 8-10 Bar chart (with confidence intervals) of one-way ANOVA.

Two-Way ANOVA

After determining that the year of study has an effect on the designer's perception of team fluency, it became interesting to understand if gender also has an effect on this perception. Research in HRI suggests that males and females exhibit different responses in the way they relate to robots during collaborative tasks (Hoffman and Breazeal 2010; Hoffman 2019). A two-way ANOVA was set up.

A two-way ANOVA is a parametric test used to determine whether there is an interaction effect between two independent variables (year of study and gender) on a dependent variable (team fluency). The interaction effect will allow us to determine whether the effect of design maturity on team fluency is different for males and females additionally to the effect of each variable independently. The 2 x 2 ANOVA analysis of variance was used to determine the main effect of gender and the interaction effect between gender and design maturity (year of study) on team fluency. Before carrying out the two-way ANOVA test, a boxplot inspection for outliers, a test of normality and a test of homogeneity were carried out to ensure that all the assumptions are met when the two variables (gender and year of study) are considered.

Boxplot Test for Outliers

A boxplot test for outliers was run to visually assess outliers in the data. One participant, 005, a male from the second year came as an outlier who had an unusually high perception of team fluency. Figure (8-10) shows the boxplot analysis of the combined gender*year of study variables. The outlier was kept and the ANOVA test was run with and without it; it was found that there was not a statistically significant difference in the conclusions which had similar results and confidence intervals with and without the outlier. In this case keeping the outlier was considered an acceptable strategy to continue with the analysis of variance.

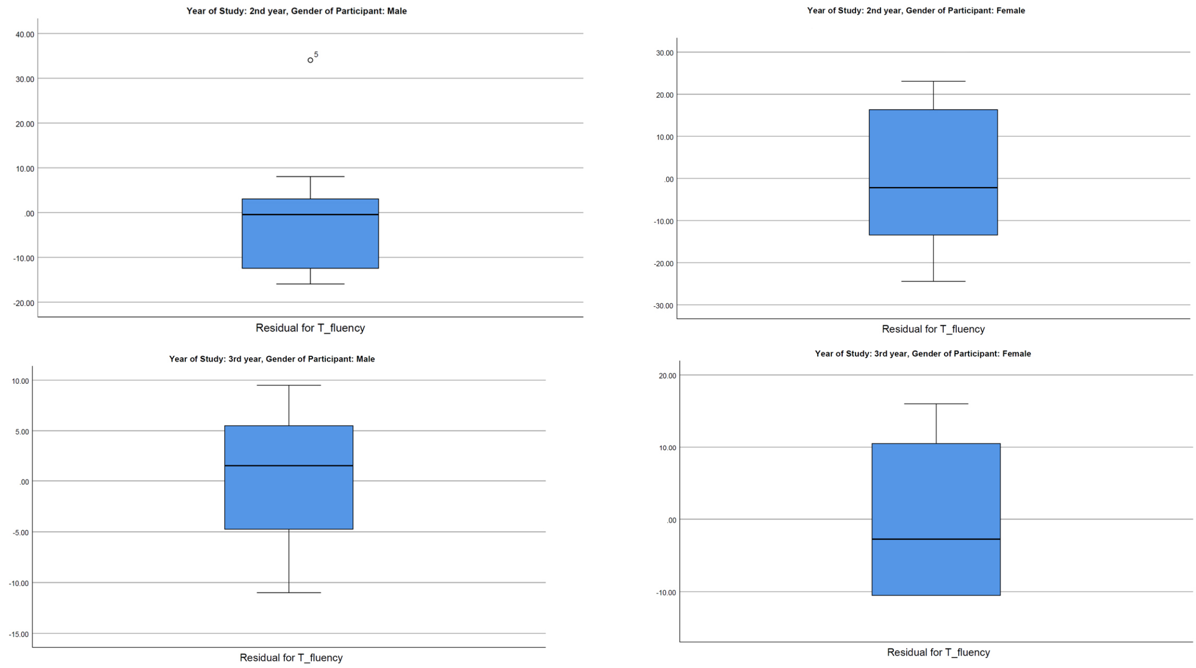


Figure 8-11 Assessment of outliers of the combined gender*year of study variables by boxplot visualisation.

Saphiro-Wilk test for Normality

The Saphiro-Wilk test was run for each combination of the two independent variables, gender and year of study. If the data is normally distributed the significance level will be higher than 0.05 ($p > 0.05$). If the data is not normally distributed, the assumption of normality is violated and the significance level will be less than 0.05 ($p < 0.05$). The results are presented in Table (8.14).

Table 8-14 Saphiro-Wilk test for gender and year of study groups and combinations

		Saphiro - Wilk		
Year of Study	**Gender**	**Statistic**	**df**	**Sig**
2nd Year	Male	0.87	9	0.11
	Female	0.94	8	0.63
3rd Year	Male	0.98	3	0.76
	Female	0.86	4	0.27

Team fluency is normally distributed for each group combination of the two independent variables gender and year of study, as assessed by Saphiro-Wilk's test ($p > 0.05$) with all values of Sig greater than 0.05 (0.11, 0.63, 0.76 and 0.27).

Homogeneity of Variance

A Levene test was used to test the homogeneity of variances. It tests that the variance of the dependent variable is equal across groups. If Levene's test is not statistically significant ($p > 0.05$) variances are equal and the assumption of homogeneity of variances is met (Table 8-15).

Table 8-15 Homogeneity of variance of team fluency

Levene Statistic	df1	df2	Sig
0.46	3	20	0.71

There was homogeneity of variances, as assessed by Levene's test for equality of variances $p = 0.71$.

Two-way ANOVA

A two-way analysis of variance was carried out to determine whether there is an interaction between gender and year of study in the perception of team fluency. The aim was determining whether the effect of design maturity (year of study) on the perception of team fluency is different for males and females. The interaction effect is represented as the product of the two independent variables, year of study * gender. The Sig column presents the significance value of the interaction effect. If the value is less than 0.05 ($p < 0.05$) there is a statistically significant interaction effect. The results are presented in Table (8-16).

Table 8-16 Test of between-subjects effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig
Year of Study * Gender	190.9	1	190.9	0.80	0.38

There was no statistically significant interaction between year of study and gender for 'Team Fluency' score, $F(1, 20) = 0.80$, $p = 0.38$. That is the effect of the design maturity, as represented by the year of study, on the perception of team fluency ignores gender. Both males and females have an increased perception of team fluency in a HIRC design scenario with higher design maturity levels. An analysis of the main effect for gender was performed which indicated that gender on team fluency is not statistically significant, $F(1, 20) = 0.80$, $p = 0.65$.

8.3 Summary

This section presented a detailed account of the criteria followed to quantitative and qualitatively code and evaluate the collected data. Statistical analysis was performed on the quantitative data to test for internal consistency and reliability. These tests were also used to find the items that contribute the most and are more representative of team fluency and to remove those which do not contribute. A further step was taken to test the internal reliability of each construct of team fluency: trust, collegiality, improvement and robustness removing the weaker items from the scale. The removed items may be tested in another design scenario before dismissing them as not being relevant to team fluency in HIRC for architectural design scenarios.

The mean and standard deviation of the overall team fluency construct and of each of its constructs were analysed and they indicate that participants' ratings do not greatly differ. The average score for team fluency was of 180 on an evaluation range that goes from 36 to 252. The maximum team fluency rate was 213 while the minimum was 151.50. The consistency and average score indicate that the test group can be considered as one formed by participants who are generally comfortable with technology and interested in learning and incorporating it into their design experience. Because this is the first attempt to develop an evaluation scale to measure team fluency specifically applicable to HIRC in design tasks, the recruited participants did not come from a robotic-specific course and were without any previous background experiences on robotic fabrication. Further studies can be conducted with designers who have experience in robot use.

An ANOVA test was performed on the quantitative data which confirmed the hypothesis that participants need a level of maturity in their design thinking before being able to incorporate other agencies into it. It also showed no significative differences in team fluency between male and female participants.

The next step is to use the results from the quantitative analysis as a background to contextualise the codes of the participants' behaviour from the qualitative information before presenting any findings. The aim of the analysis is to allow for a descriptive interpretation of the data results which can enhance the understanding of HRC during the architectural design process. The findings of the exercise are described in the following section. The reporting includes the participants' accounts for each of the team fluency related themes and a theoretically informed interpretation, informed by ANT is also discussed.

Chapter 9 CASE STUDY: REPORTING FINDINGS

9.1 Introduction

This chapter presents the findings on key human factors affecting team fluency in HIRC design teams. An ANT perspective of 'following the actors' (Latour 1987) was used throughout the analysis which allows consideration of all the non-human actants that are part of the 'robot' but which generate diverse feelings and impressions in the participants.

The interviews represent the main data collection tool. The analysis and evaluation of the quantitative questionnaire on team fluency, presented in section 8.2.3, has been related to the qualitative analysis and coding of the responses to the interviews, field notes and video material described in sections 8.2.1 and 8.2.2. The themes with the lower scores in the quantitative questionnaire were analysed in relation to participants' actions to understand possible causation and how specific circumstances may have influenced participants' perceptions of team fluency. Additionally, anecdotal findings were correlated and confirmed through the qualitative coding of the semi-structured interviews. The findings aim to present how participants made decisions as designers after seeing the actions from the robot and questions what is constant in their design and their objectives. The analysis specifically looked for shifts of agency: those moments in which participants transfer design agency towards the robot partner either by changing their initial conceptions about how the design would be realised or by enabling more agency to the robot as the task progressed

9.2 Team Fluency

The notions described in chapter 4 were used to evaluate designers' sense of human−robot fluency during the design task. The findings include each of the main notions and several downstream measures. New team fluency sub-themes, outside of the ones laid out in the initial constructs appeared throughout the coding of the data. The most relevant new sub-themes, constantly mentioned during the evaluation of team fluency, are the participants' design background and the results of the design exercise.

9.2.1 Trust

Trust was evaluated in relation to three main themes: robot elements, human elements, including design background and previous experiences, and external elements related to the task. Trust was evaluated mainly from the perspective of the participants through the questionnaires and interviews. Trust was continuously recalibrated through the design task and trust in some of the elements may not imply trust in the robot or in the human−robot team.

9.2.1.1 Human elements

The elements related to the human part of the team have been grouped under the metrics of human performance, human experience and human safety. Human performance is measured from observable human actions, decisions taken during the design exercise and their implementation. Self-measured metrics are also used in questionnaires.

Human performance

The majority of participants elaborated on their performance. They felt comfortable working with the robot. A small number of participants mentioned not being ready to incorporate the robot into their design process as it was a new tool with different, unfamiliar constraints. Fourteen participants found incorporating the robot was a steep learning curve, first to understand it and then to incorporate its characteristics into their design. However, they acknowledged that this process only needs to be done once and then it would expand the possibilities of their design process. There is agreement amongst the participants that as the task progressed, human performance improved and that more experience would be beneficial.

> *"The problem is not the robot. The problem is the gap between the user and the robot. Additionally, the robot takes such a steep learning curve. The upside is the potential of what you can do once you learn it"* CS2-012.

Participants' mental models and preconceived notions affected their trust and expectations in the robot. Most participants were surprised by the smooth, controlled motions of the robot. It appeared that they were expecting some jerky, fast, monstrous motions as often portrayed in the movies. Another preconceived notion was that robots can move to act against humans. The robot's stationary position on the floor made participants feel safe and reassured.

> *"The fact that he doesn't move from his position on the floor is a lot less scary"* CS2-005.

> *"When I think of a robot, they move around. If it moved, I would be very scared"* CS2-018.

Human experience

The quantitative analysis presented in section 8.2.3 demonstrated that a level of design maturity is required before being able to cede agency to the robot. This is consistent with the reactions and behaviours of participants. Younger participants engage in a playful way with the robot and are less interested in the feedback and rigor. Mature participants use the feedback, are constantly consulting with the robot, do less manual jogging and plunging, and are more aware of the robot's suggestions and generated paths. Additionally, they are more engaged in making models and experimenting with them; both physical and digital models.

The most positive human experience of designing with the robot was the different perspective that it provides over the design process. For 15 participants designing with the robot allowed them to put some distance between themselves and their design process. This was appreciated for two reasons: 1) as the design process advances, designers get more embedded in the details and can lose perspective on the overall picture; the robot gives a general overall perspective by showing what is exactly happening to the shape, 2) the use of parametric and form-finding tools has brought an additional layer of complexity to design, including non-Euclidean spatial configurations. These shapes are more difficult to discuss and understand purely on the basis of optical perspective. The robot increases understanding of the form and the material.

Overall the human experience was positive, working with the robot was mostly rewarding and the robot perceived as an enhancer of human action. Robot motion manipulation was empowering and motivating.

> *"I couldn't believe that I could really tell the robot what to do, it was something like powerful"* CS2-019.

Prior experience and knowledge received attention from participants. Most of them (18) suggested that prior experiences would have made them feel more natural and more experience working with an industrial robot would be beneficial and allow them to exploit their characteristics during the design process.

Design background

The design background of participants, specifically whether they are used to making exploratory models throughout the design process or just at the end (presentation models), was one of the most influential aspects on how they relate to the robot. Participants who are accustomed to the use of models to represent a preconceived idea struggled with the feedback and the uncertainties of the collaborative design result.

> *"When we're designing in our design projects, we design the finished product whereas for this one we were designing something in the beginning and we didn't know how it would turn out"* CS2-014.

They tend to feel precious of the physical models, which are made to *"see how it looks like".* They refused to modify the material and explore through it. Five participants noted that they have not been taught architecture in this way, hence their hesitation to explore their designs through models. This results in finding the use of the robot problematic in earlier stages of the design process and a preference for using it to make a final model. Participants who are accustomed to the use of exploratory models (14) are more receptive to the design and robot workflow. They see the robot as an aid to do models and iterate on them at a faster speed

Human safety

Responses to the questionnaire on trust rated human feelings of safety and comfort during the collaboration with the highest scores. The safety aspect was evaluated with three items, all of them scoring above 6.2 out of 7. Participants' comments suggested their main safety concern was to avoid being hit by the robot, during the task and after it. Furthermore, 12 individuals discussed the robot being was aware of its surroundings and of the human team member as something that would increase their trust. However, the robot's safety features, specifically the panic button which stops it immediately, made them comfortable and trusting of the robot. The cage and the locking mechanisms had the opposite effect of reducing their trust.

Human elements summary

Participants felt safe and comfortable working with the robot, even if bothered by some of its safety protocols (cage, locks). Understanding technology is empowering for humans and higher levels of understanding are desirable as they enhance the human sense of accomplishment. Designers were inclined to trust the robot; however, their design background, acceptance of digital design workflows and of making exploratory physical models throughout the design process versus a final representational model affected their reactions and interactions.

9.2.1.2 Robot elements

"While trying to make robots human, researchers have sometimes overlooked what makes robots special" (Groom and Nass 2007, p.494).

Data analysis revealed that robot elements could be grouped into four major lower level themes. Two of them are consistent with the literature and have appeared in other HRI studies: robot performance and robot physical attributes (Hancock et al. 2011a). The other two: robot digital attributes and the robot feedback into the design task emerged from the design exercise. Themes were prioritised on the basis of the frequency in which they appeared in the data analysis.

Robot digital attributes

The digital attributes of the robot were one of the parameters that received most attention. The design task and the workflow were designed to reduce workload and make them accessible for designers. However, translating human thoughts into machine motions was a highly discussed topic; specifically, knowing how to translate design thoughts into robotic actions that the robot can effectively understand and execute.

> *"The main obstacle to design with the robot is the interface and difficulty in translating human thoughts into machine movements"* CS2-001.

Not knowing the code and scripting, although not required for the task, was worrying for the majority of the participants who felt they could not use the robot without help, nor could they instruct it freely.

> *"I had challenges with the code. If I know how to overcome that, the robot would be a great partner"* CS2-002.

This differs from collaboration in manufacturing or other tasks in which robots can be pre-programmed for the task, designers want to explore.

> "*Jogging and designing with the robot is fun; the coding and programming not*" CS2-003.

Robot feedback into the design task

The feedback was one of the most successful attributes of the robot (Figure 9-1), with one of the participants going as far as to say:

> *"The feedback is the best thing about working with the robot. It allows me to see variations between the digital explorations and what happens in the real world: being able to see them side by side and the points that match and don't match. It gives you a*

quantitative understanding from which you can then investigate further" CS2-005.

Most (24) agreed that the feedback provided by the robot is more efficient in detecting differences than people and it makes the design discovery process more scientific (quantifiable). Even participants who were less interested in the material's behaviour found the comparison between the digital and physical extremely interesting.

> *"When you have something in mind and you can compare with a physical one that's very helpful, because you can have accuracy"* CS2-011.

> *"It [robot] can see things that with the eye I can't see. And I think that the mind is tricky sometimes"* CS2-019.

The feedback was most exciting when the digital and the physical were not far off, and participants could see the scan and realise the model was closer to their design than they had anticipated. During the research task, most of the time the participants are not aware of how close or far they are from their intent unless some extreme deformation or tearing happens. The accuracy and insights into the material deformations that the scanning and physical-digital comparison provides are equally attractive to mature and younger participants and to more material or more digitally-oriented participants.

> *"The feedback was very useful. It can give you precise data that you can't judge by eye and it also changed the way I was looking at my design. It allowed me to see things in a different way"* CS2-012.

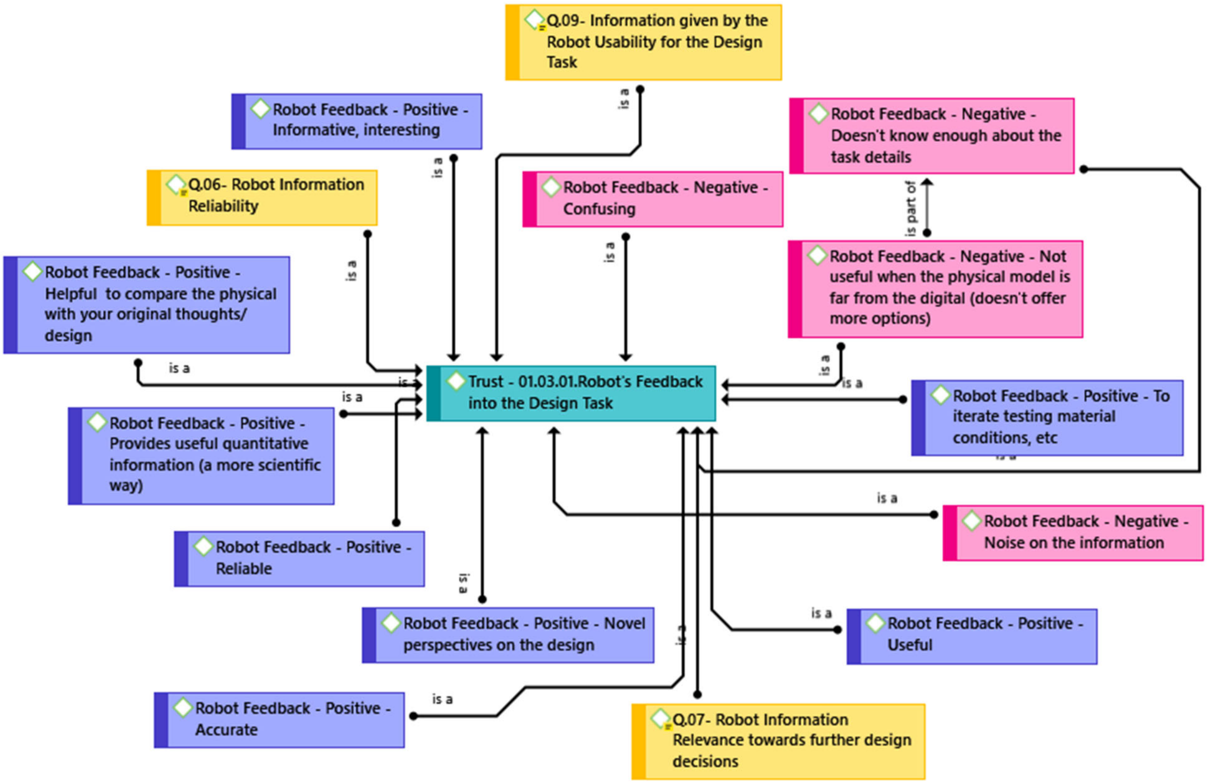


Figure 9-1 Robot feedback positive and negative attributes as described by participants. Blue indicates positive, red negative and yellow questionnaire questions.

Robot physical attributes

The physical attributes of the robot, its size, appearance, and how it behaves, were positively received (Figure 9-2). They did not represent a cause for concern to participants who did not seemed uncomfortable about them. This is contrary to the initial hypothesis that the large size of the robot may result intimidating or provoke fear and distrust (Phillips et al. 2011; Charalambous 2014). The size made it mostly attractive. However, its heaviness and colour less so.

> *"It's just big, and that makes it more compelling to use. The only thing I would change is the colour"* CS2-001.
>
> *"I would trust the robot more if it wasn't that heavy"* CS2-027.
>
> This could be attributed to the students' intrinsic knowledge that the robot is a big,

dangerous machine. Hence, the fact that it looks like one does not bother the participants. However, humans are hardwired to look for behavioural clues in other humans and non-human actors. Robot arms do not afford us this legibility; human instincts looking for clues triggering actions have to remain passive and expectant. This was pointed as a negative attribute. Adding a face to the robot or a laser pointing to where it is going to move next would be desirable traits to make it more trustable to co-workers. Most participants would like the robot to be enabled by sensors to make it aware of its environment aiding to the legibility of its behaviour. This is consistent with previous research in HRC which points out that fluidity and action-prediction are key for effective human–robot collaboration (Charalambous 2014).

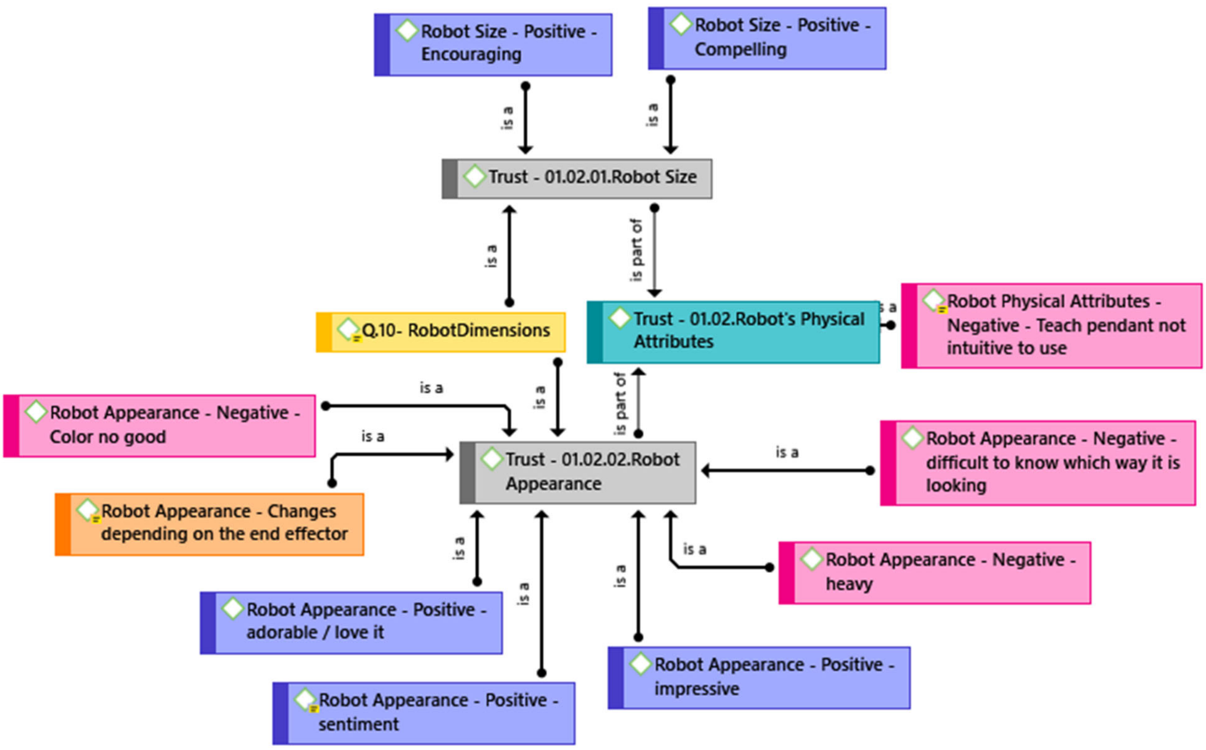


Figure 9-2 Robot physical attributes. Blue indicates positive, red negative, orange neutral and yellow questionnaire questions.

Robot performance

The evaluation of the robot performance (Figure 9-3) was further divided into two sub-themes: trust in the robot motion and trust in the end effector. The reliability of the end effector has had an impact on trust in the robot in HRC in manufacturing tasks (Charalambous et al. 2016). Separating both seemed more appropriate, even if the robot is perceived as a single agent comprising all its components.

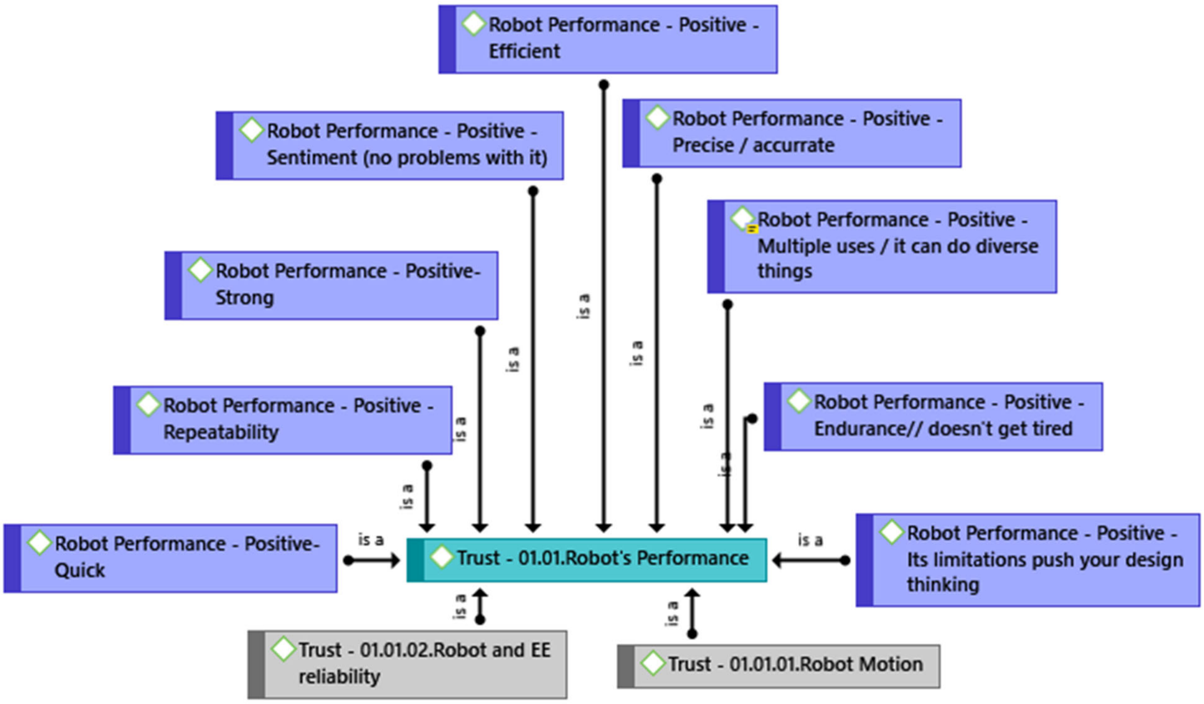


Figure 9-3 Attributes of robot performance. Blue indicates positive.

Robot motion

The majority of participants elaborated on the movements of the robot. They mainly used adjectives like *"elegant*", "predictable", "precise" and *"controlled*" to describe them (Figure 9-4). Robot motion was evaluated as comfortable to most participants (M=5.7, SD=0.1). The speed was also comfortable (M=5.6, SD=1.0). It was suggested that robot motion aided human trust.

However, most (17) participants found motion planning a time-consuming task.

> *"The biggest weakness of the robot is the amount of time the process takes"* CS2-012.

The robot needs for very precise information and the fact that even with a good path it may reach joint limits and positions have to be re-planned was the main obstacle for the flow of the design collaboration.

> *"We had to consider the axes movements and also the limit distance that the robot could reach; the quantity of points and the distance between them influenced the speed and uniformity of the cut. We had to flip the coordinate planes direction so the robot could reach all the points"* CS2-014.

Another challenging aspect was having to think about inserting specific elements, outside the design, to generate a successful robot path (i.e. extra points, curves for air moves, to orientate the tool, etc.). These additional elements were confusing for the participants. From the second session when participants were recording a path using the teach pendant, they would spend a lot of time doing complex motions to reach positions in a certain axis orientation. However, participants would only record the final tool positions. This invariably resulted in the robot following a different path from the one used by participants. Their later comments generating the robot path reflects the same motion planning problem.

Path planning is particularly important for collaborative design tasks which are exploratory, and where paths cannot be optimised for a single solution the search for diverse motions and approaches to the material and the design space is inevitable. It can be that participants think of the robot as a machine of endless possibilities and the limitations are unexpected, hence problematic. However, some found the limitations encouraging to explore novel solutions and possibilities.

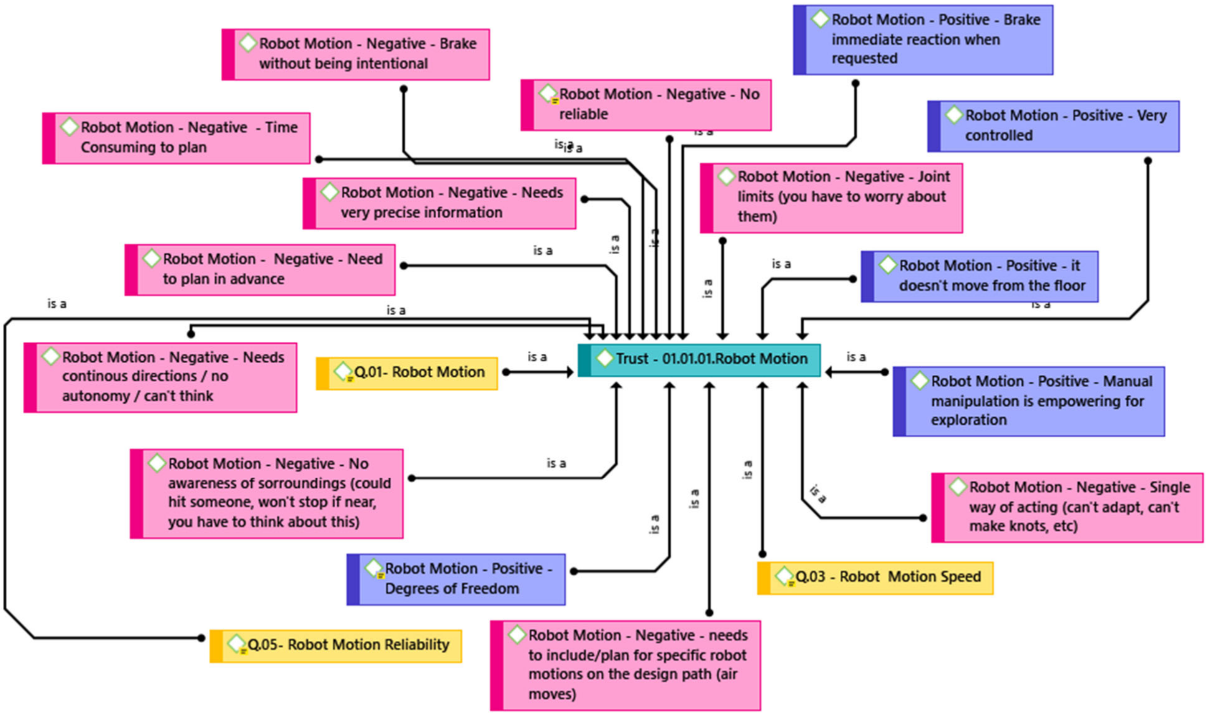


Figure 9-4 Robot motion attributes. Blue indicates positive, red negative and yellow questionnaire questions.

Robot and end effector reliability

The end effector is a crucial part of the robot, without an end effector the robot cannot do anything. In a design scenario it makes the robot versatile, allowing multiple uses for it, but the reliability of the end effector can affect human trust in the robot (Figure 9-5). Multiple uses also mean experimental end effectors which may not be as robust as the robot. The actions of the robot (M = 5.7, SD = 1.2) were evaluated as considerably more reliable than those of the end effector (M = 4.9, SD = 1.4).

> *"The robot is very reliable. Sometimes [problems arose] because of the impact of the blade, but that was the tool not the robot. For my model I didn't have any problems; the robot was doing what it was meant to do"* CS2-014.

The participants were comfortable with the speed and motion. Designers were generally interested in knowing more about the end effector designs.

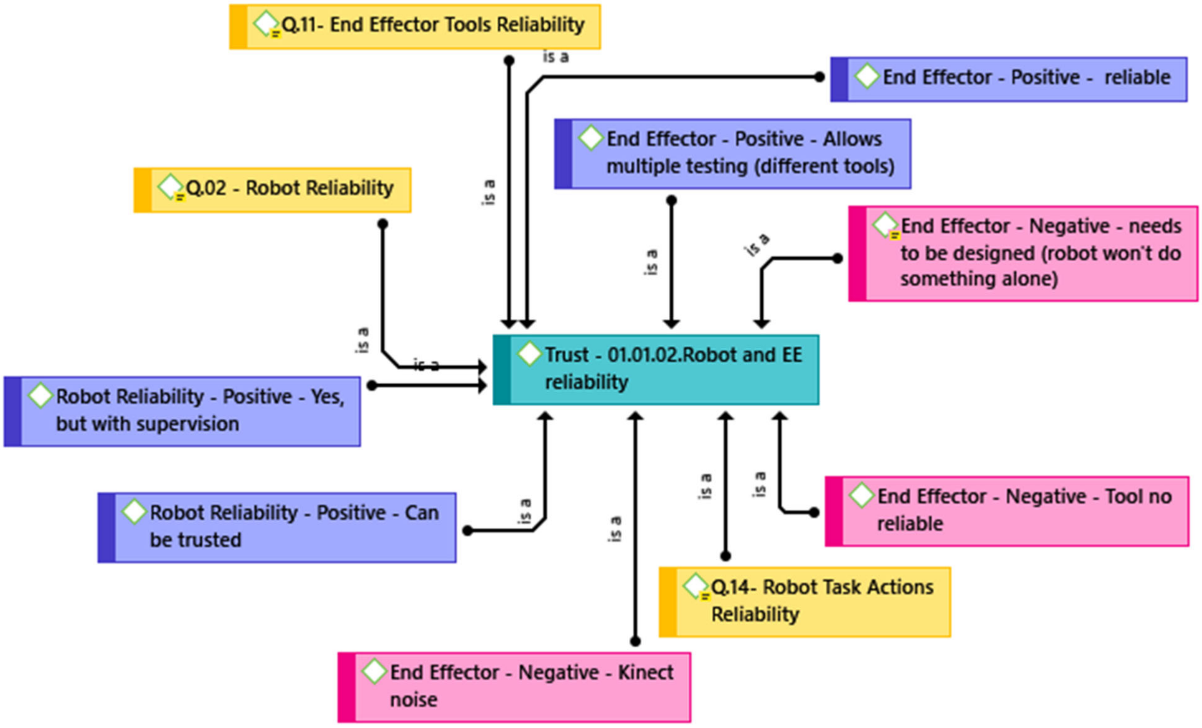


Figure 9-5 Evaluation of the end effector by participants. Blue indicates positive characteristics, red negative and yellow questionnaire questions.

Robot elements summary

Different robot elements are relevant in order for designers to trust in it as collaborative partners. Common parameters from the literature like the type, size, proximity and behaviour of the robot do not affect designers' trust. The main issues affecting the flow of the design task and their trust in the robotic partner are:

1. Digital attributes. Translating design thoughts into robot motions. This as opposite to a partner who understands your goals and helps achieve them. Literature on HRC, including collaboration with industrial robots, rarely speaks about the digital aspects of programming and interacting with the robot; this may be task specific as designers need to be continuously exploring and testing rather than relying on a pre-programmed robot for a defined task.

2. The lack of transparency and legibility of the robot's behaviour. A signalling system between robot and human teammates could be implemented to ease collaboration and make their behaviour and motion plans legible to their human partners.

3. Lack of sensors. Awareness of its environment and itself will promote trust in the robot from the human co-workers.

4. Design exploration. This is a divided area; some participants find that the robot requires precise instructions which limit its possibilities for design explorations as designers would not have this precise information during the early stages. Others consider the playfulness of using the robot, either by manually jogging or quickly iterating different motions, positive for exploratory design.

5. Ceding agency. Designing with robotic thinking, considering its characteristics, allowing more agency to the robot yields better results than trying to control everything. Comments include doing more playful designs, bigger curves which can deform more, etc. with the aim of allowing the robot and the material more agency.

> *"If the design is too constrained, the possibilities to explore with the robot are less. The design needs to have some openness to it, so to explore with the robot"* CS2-002.

6. Reliability of the end effector. It did not appear to have an impact on trust. This seems a context-specific aspect that has not appeared in previous literature. This is of particular relevance to design HIRC tasks in which end effectors are flexible and varied (i.e. different from single task industrial grippers, etc.).

7. The robot **not being too smart** was often mentioned as a cause of trust.

A thing to note is that some of the positive comments regarding the robot performance were limited to remarks shaped by low expectations of the agent *"the robot did what it was supposed to do"*, *"the robot worked as expected"*, *"the robot did not mess up"*.

9.2.1.3 External elements

External elements are mainly evaluated as those related to the task. This sub-theme looks at task complexity, type and physical and environmental factors that influence HIRC.

Environmental factors

Factors outside of the task most mentioned by participants as influential to their relation with the robot were:

1. Security elements. The cage and locking mechanism as elements that detach from the robot experience and interfere with the flow of the exercise. Although participants acknowledge they are meant to keep them safe they feel they are detrimental to the interaction.

> *"The only thing that I feel is weird about the robot is the cage and all that's done supposedly to protect you from it; I felt that is the thing that detaches you from it"* CS2-017.

2. Accessibility. Beyond the design exercise lack of accessibility due to institutional reasons (limited to specialist courses) or generally being less accessible than other fabrication machines (3D printers, laser cutters).

> *"Is like a precious machine we cannot touch, we can only peek through the window and wonder what is it doing"* CS2-019.

Task interaction with the robot

The task in relation to the interaction with the robot was evaluated high in the questionnaire (Figure 9-6) (M=5.6, SD=1.0) and during the interviews. Participants felt the robot is very good for some aspects crucial to the success of the design task (i.e. cutting, pushing, quantifying deformations) such that it could not have been done otherwise.

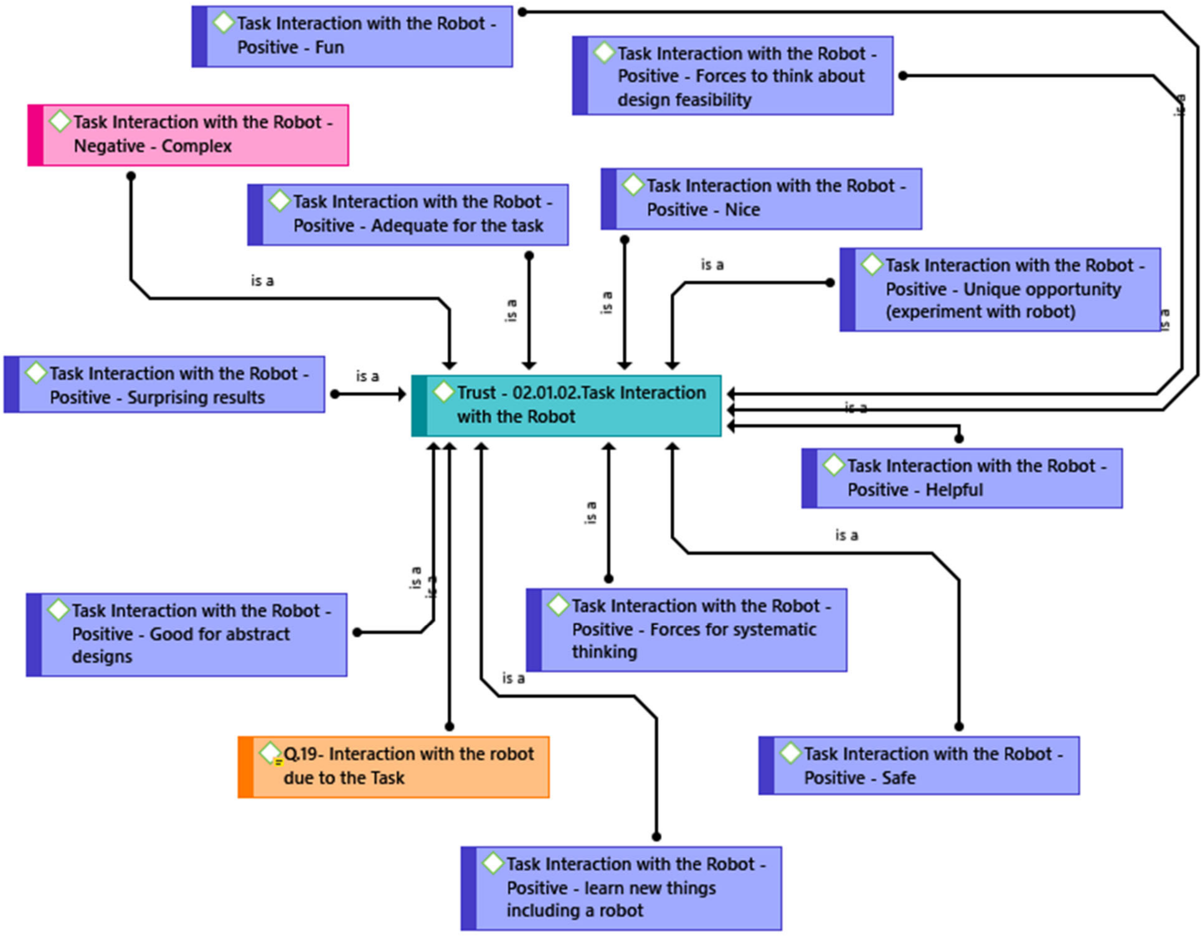


Figure 9-6 Interaction with the robot. Blue indicates positive characteristics, red negative and yellow questionnaire questions.

The positive aspects with most comments were:

1. It forces systematic thinking, including considering feasibility and 'machinic' sensibilities from early stages.

2. Interacting with a robot is fun and playful.

3. Complex results can emerge from simple commands, which enhance iteration and testing.

A crucial negative aspect is the complexity of the robot, its motions and characteristics that have to be considered in the design. However, participants would understand that the steep learning curve which can put them initially off only needs to be done once.

Task complexity

The complexity of the task was considered adequate for this exercise and the task interesting, fun and enjoyable (Figure 9-7). Participants felt comfortable with the level of coaching and guidance received which allowed them to feel empowered to perform the design exercise. A negative aspect mentioned by most participants is how the design takes most of the time you spend with the robot. It was necessary to disentangle whether more experience was required with the robot or with the digital design tools.

> *"Designers have to think in advance about the motion. Designs have to be thought of in a way in which they could be done by a robotic arm"* CS2-002.

Two additional sub-themes were coded under task complexity from this observation:

1. Task complexity related to the software. Perceived as challenging and time-consuming by most participants, mainly with regard to the generation of robot paths from their designs. The design, simulation, scanning and comparison were not problematic.

2. Task complexity related to the design workflow. The main source of struggle in the design process, not related to the robot itself, was in designing a parametric system of 2D curves rather than a 3D shape, as participants would normally do. Designing the 2D system of constraints which will define the final form requires a different approach to design and a systematic way of thinking that can allow the designer to explore the space of possibilities rather than imposing a 3D shape. However, adopting this way of thinking was not easy for the duration of the exercise. Additionally, this is not the way the students are traditionally taught.

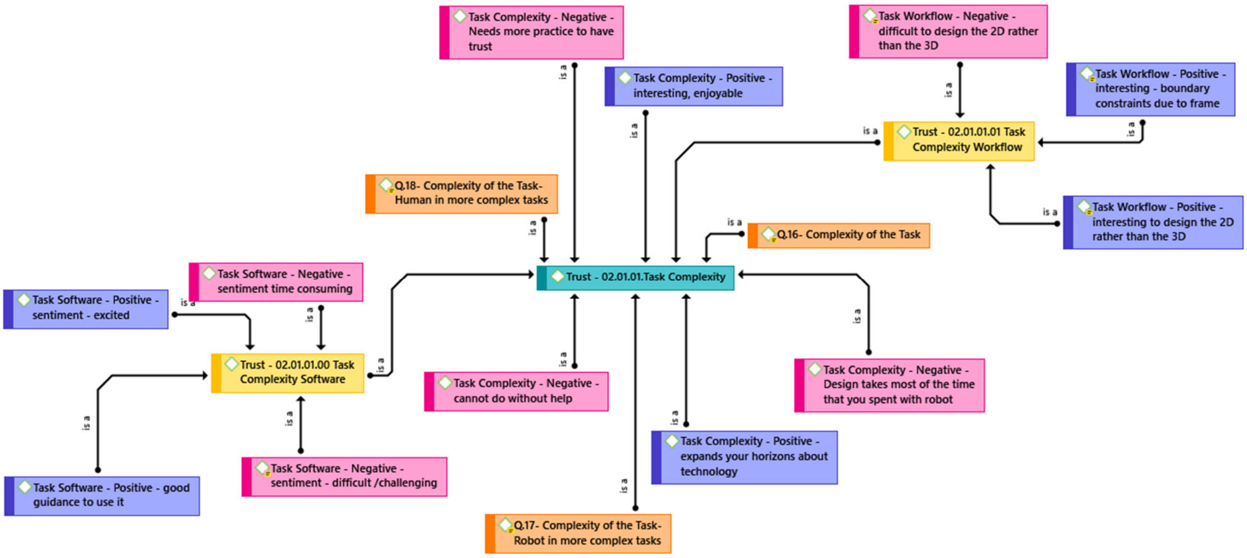


Figure 9-7 Negative and positive aspects perceived by participants of the task complexity and its sub-themes.

Task results

Participants' trust is highly influenced by the robot successfully completing the task. Most blame for unsuccessful results is attributed to the robot or to the human having to communicate with the robot, even if the design and the setup curves are the cause of unsuccessful results. The final design shape of most participants (16) was similar to the digital simulation resulting in high satisfaction and levels of trust. Participants' trust decreased as the results were further from their initial designs. The worst case, in which the robot tore the shape after a second scan, resulted in high levels of frustration and the lowest trust in the robot.

9.2.1.4 Trust summary

Trust analysis reveals designers' acceptance, trust and comfort working with the robot as design partner. The physical and digital aspects of the robot were not trust deterrents, although, participants would not feel comfortable with a more complex task. The main trust issues that designers face when working with robot arms are:

1. **Translating their design thinking into robot motions**. This is a dual problem. On the one hand the exploratory nature of the design process requires an understanding of robot motion

and behaviour rather than relying on an expert programming it beforehand. On the other, designers are not traditionally taught design in a systematic, exploratory way that can allow them to describe their design ideas to a machine. Additionally, designing the 2D rather than the 3D became an extra challenge to the task. This was a twofold challenge: first, they did not know the result from their 2D curves; second, they did not know the result from the robot plunging.

2. Design decisions. For the robot to perform its tasks designers needed to decide whether to follow the suggested robot solutions or to specify their own, execute the process and then verify the outcome.

3. Trust dynamics. During the design process the levels of trust were constantly adjusting and modifying, for some parts of the task the participants fully trust the robot (cutting) whereas for the detailed aspects of the design, they liked to 'massage' the shape themselves. Regardless of whether the robot achieved the design target, designers would rather end up with a different shape than allowing the robot to have the last word.

4. Robot smartness. Designers trust the robot because they see it as 'non-intelligent'. However, constant with the literature, in the cases in which something went wrong (fabric ripping) humans would not easily trust the robot again after they feel it has failed them.

9.2.2 Collegiality

Collegiality is measured by behavioural metrics related to the participant's interaction with the robot. Attitudes on interactions were recorded in the videos of the task and in the field notes. Additionally, five indicators in the questionnaire were related to three downstream measures: robot's contribution, teammate traits and partnership which compound to evaluate collegiality in the human−robot team.

Robot's contribution

The robot's contribution to the task was generally acknowledged as positive and participants agreed the things the robot did contributed to the success of the task, although the human contribution was seen as larger (Figure 9-8). The following five attributes were the most discussed as the main positive contributions of the robot to the design task:

1. Encourages creativity and novel ways of design thinking.

2. Contributes to rigorous experimentation. There was a widespread feeling amongst participants that digital tools offer great amounts of flexibility such that formal exploration becomes easily ‘uncontrolled’. Working with the robot forces them to include physical constraints from the material and the machine into the design process from early stages. The material’s outcome and its process become agents from the beginning. The rigor, introduced by the robot, to the experimentation and form-finding process is perceived as something that increases its repeatability.

3. Allows the designer to see the bigger picture. Working with the robot allows participants to put some distance between the design and the designer, allowing for different perspectives of the design to be considered and hence new ideas can form in the designer’s head out of these unexpected views. They feel that designers tend to get embedded in small details and forget about the bigger picture.

4. Non-human ways of exploring the material. The lack of sensors gives more freedom to the robot allowing the exploration of material formations that humans might try to avoid as they would be concerned of breaking the material or deforming it too much. The robot does not have any of these constraints. It encourages testing and being more adventurous and extreme with the material.

5. **Precision, versatility, speed, strength** and the robot’s limitations pushing the design thinking were the most appreciated robot traits in descending order, with each mentioned over 15 times.

“We don't have limitations in the way we've learned to model. Working with something

that does call for safety and limitations it's useful because it pushes the way you think" CS2-012.

and

"It gives you a kind of freedom to create, even with its limitations" CS2-010.

The robot allows the participants to reach the initial design intent with more precision while having more control over it. It allows faster iteration of the process. The robot can perform parts of the task (cutting) faster than participants would and push the material further; it complements designers during the exploration process.

"It's like a third hand that can be stronger, precise and doesn't get tired" CS2-003.

Efficiency and repeatability were also mentioned, albeit less.

Three negative aspects associated with the robot's contributions were the most discussed:

1. The lack of sensors. Lack of sensors is mentioned here again but in relation to the task. It may result in the robot applying excessive pressure so that the material breaks whereas a human teammate would stop. Humans can see and feel, while the robot lacks human intuition, although the abruptness of the robot with the material was also considered a positive contribution.

"Robots lack human intuition, when you can see, actually, that something will break. You feel how much you should push and robots doesn't have it" CS2-008.

2. Machine limitations. The robot cannot push up, twist or make other motions unless previously prepared to do it. It cannot improvise during the exploration process.

3. The constant need for human directions, which can lead to increased human workload.

> *"The robot can't think some things. You have to feed the robot all the time in order to produce things. It doesn't have the mind to think maybe I'm doing something wrong, but humans have to give these directions all the time"* CS2-007.

Teammate traits

This downstream measure is meant to evaluate the perceived traits and character of the robot related to it being a team member. Additionally, naming the robot was considered an indication of teammate traits. The literature suggests that people who give the robot a female name see it as a subordinate, whereas those who give it a male name see it as a partner with desirable teammate traits (Benfield et al. 2007; Kindberg and Jones 2007; Keay 2011). Animal, and cartoon names (i.e. little chicken, Mr Bean, etc.) were considered neutral.

The robot was evaluated as an average teammate (M=4.1, SD=1.6). Its attributes were seen as complementary to those of the designer and beneficial to the design exploration process. However, its inability to learn about the material and the cutting and plunging processes reduces its teammate status. A total of 18 participants gave the robot a male name, three gave a female name and four gave neutral names.

Partnership

As described in section 4.3.1.3 this composite downstream measure has been taken from an adaption made by Hoffman (2013) of the *"Working Alliance Index"*. The partnership measure is made of two subscales: the "bond" and the "goal" subscales.
In the bond subscale the robot was perceived as a partner by most participants (M = 5.6, SD = 1.4), who also claim they like the robot even if the robot does not like them.

> *"He doesn't like me; I like him"* CS2-009.

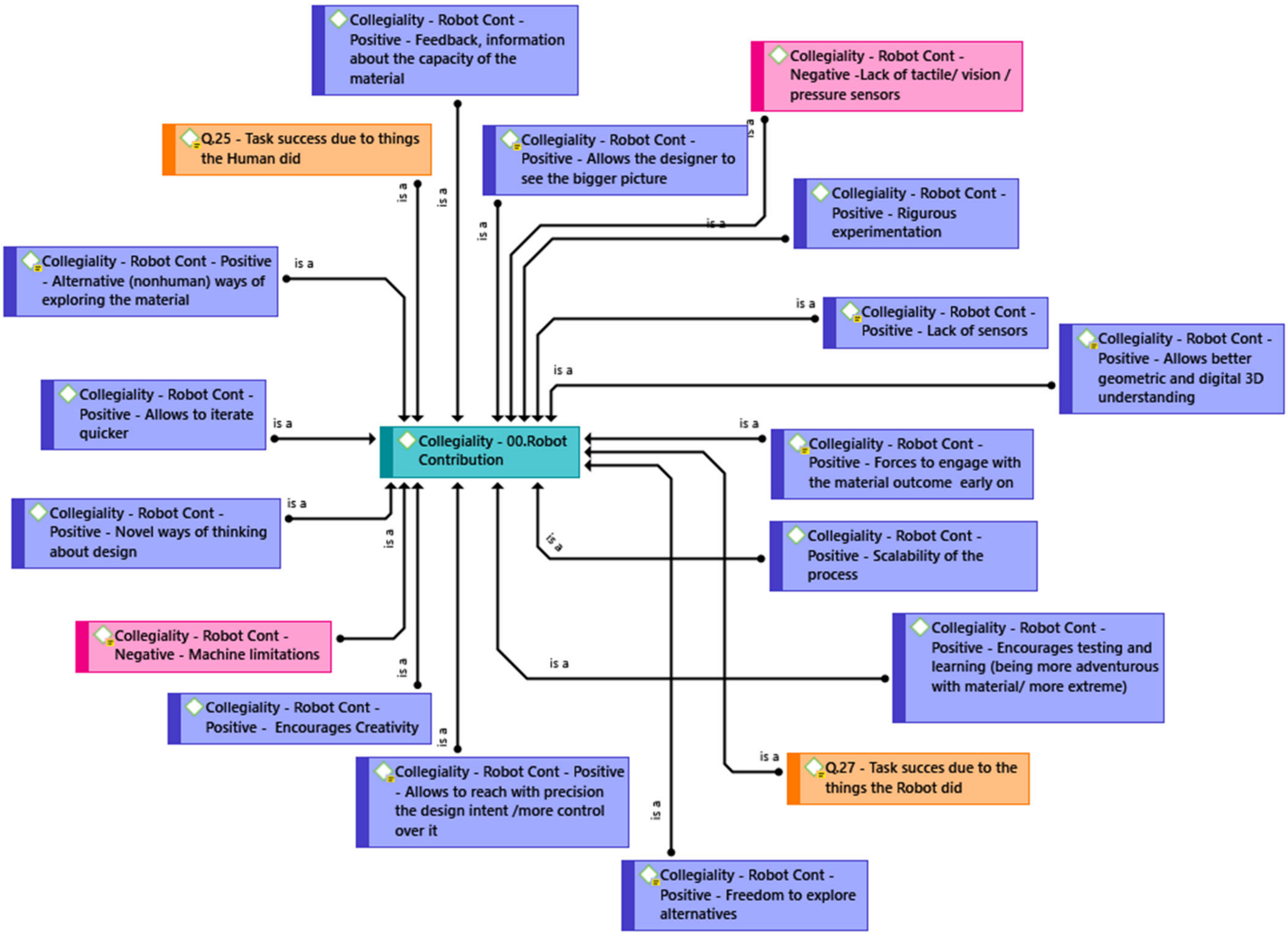


Figure 9-8 Positive and negative contributions of the robot as coded from the data analysis.

Positive comments about the robot partner included participants reporting how it *"allows a lot of room for experimentation*" (CS2-010) and participants saying that they had emotional responses that went from *"first scared to curious to feeling empowered by being able to work with it and seeing it do their design"* (CS2-012). And one went so far as to claim that *"by the end of the session, the robot was understanding me; he is adorable. I now love talking to him"* (CS2-019). Another participant commented *"I like the robot a lot. I love the robot"* (CS2- 009). Figure (9-9) shows the positive and negative emotional responses to robots.

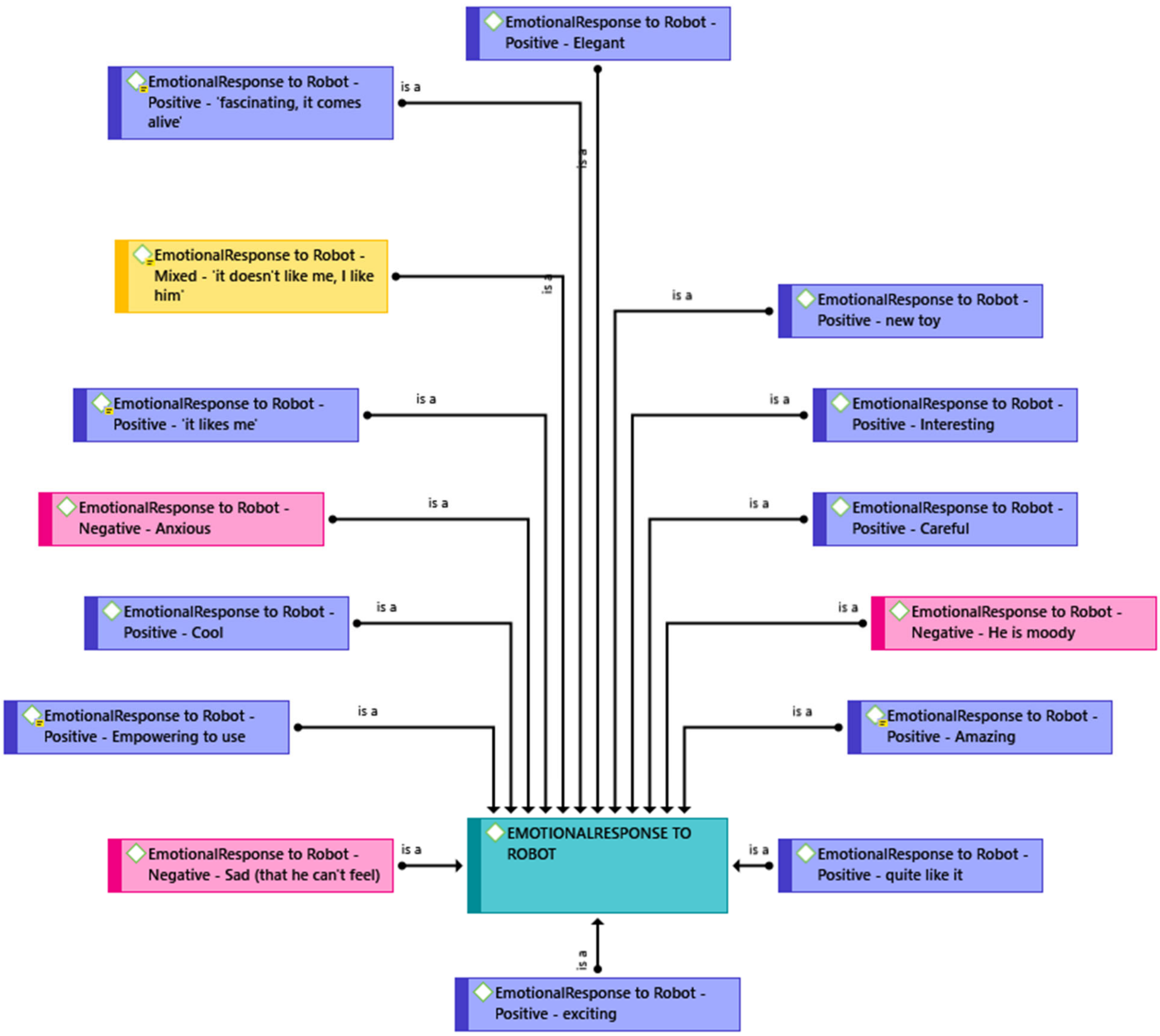


Figure 9-9 Emotional response to robots.

In the goal scale it was generally acknowledged that the robot helped participants perform the design task better. The main way in which the robot helped participants was by providing an understanding of the material's behaviour; the quantifiable information allowed them to know where to cut, push and by how much and do it precisely. This, along with the mapping of the digital and physical outputs, are the ways in which the robot was useful to achieve their design goal. The robot also opened different understandings of the material.

Collegiality summary

Additional indicators that were not directly measured, but mentioned by the participants during the interviews, include:

- The robot performing well as part of the team
- The robot doing its part of the task successfully (participants will indicate that they failed in how they instructed the robot, while giving credit to the robot).

These measures were not initially considered as they have not been successfully demonstrated in previous HRC research studies evaluating fluency (Hoffman 2013a). However, for the design scenario these topics were constantly discussed during the post-task interviews. Further study is merited to include these measures with respect to the perceived fluency of the HRT.

The robot received average scores for its contribution to the task, (M = 4.5, SD = 1.4) and for its teammate traits (M = 4.1, SD = 1.6). Due to the characteristics of the industrial robot a lower score on teammate traits was expected. The higher scores on the robot's contribution could be due to the low expectations that people have about robots and its generally reliable functioning and traits such as precision, speed, and strength which humans lack and were seen as positive contributions. Additionally, in some cases manually jogging the robot, although not intended, became a very playful source of discovery. Participants became engaged in playing with the machine and the material and through scanning discovering and understanding their actions. The playfulness of the machine became an alternative positive path for design discovery.

On the scores related to partnership, the results for the robot between the goal subscale and the bond subscale do not show any significant differences. This is different from what was expected and from results in the literature where the score of the goal scale has been significantly lower to the bond score (Hoffman 2007; Hoffman and Breazeal 2010). One possible explanation for this phenomenon is that the feedback given by the robot was generally scored high by the participants and described as "*one of the most useful things of the robot*" (CS2-005). The usefulness of the feedback could have increased the goal score as participants felt that the robot helped them perform better on the task. It is acknowledged in the literature that bonds take long to form, but experiments are generally done in one session. Having the training session and the task session as two separate ones could be an explanation for participants' feelings of forming a bond with the robot partner.

A surprising effect of the case study was to find a high number of self-deprecating comments and comments indicating worry or stress for the weak human performance in relation to the robot's strong performance. Several participants remarked how the robot performed exactly as expected or better, whereas they considered they were not performing at an adequate level. Marquez et al. (2017) describe this as the irony of automation being the exacerbation of the human error.
Remarks included:

> *"He's doing his part of the contract, well it's just the fact that I've f**** up everything"* CS2-009.

> *"Robots will do what you tell them to do not what you want them to do, and we told him the wrong things"* CS2-028.

> *"I think the problem is more like my brain can't process where the X is, so I cannot tell the robot"* CS2-020.

The emphasis in the comment of this last participant is on her brain rather than on the machine. While it is out of the scope of this dissertation, further work to explore designers' reactions to a smart machine is of interest. A smarter robot that could learn from the material and the cutting and plunging processes. This leads to a dichotomy in which smarter robots may be better teammates but could also increase negative human feelings about their own performance. Humans need to feel more accomplished than the robots they are working with (Hoffman and Breazeal 2010; Hoffman and Weinberg 2010). This signals towards the need to achieve the correct balance between increased robot knowledge and the discouragement that might result to their human partners.

9.2.3 Improvement

The human team member undergoes a learning curve of adapting to the collaborative task and to his or her robot partner. Although, in this task the robot is not learning nor adapting it is interesting to estimate the relative contribution of each team member to the improvement of the team and how the human perceives the robot performance through time. The questionnaire had three instances to evaluate improvement, one for improvement of the team, one for human improvement and one for robot improvement. It is important to note that after the second training session, participants were allowed to practice and jog the robot as long as they wished to do it. Participants interested in training digitally or physically with the robot could show up at any moment. This allows participants to consider improvement as a relative measure over time coded from their interview answers.

Human improvement

There was a general sense of human improvement (M = 5.4, SD = 1.4) (Figure 9-10). The main areas where improvement happen are:

1. Ceding agency to the robot. Design iterations increasingly considered the robot's characteristics and participants designed with more 'robotic' thinking. This yielded more satisfactory results.

> "The limitations of the robot are useful to push the way you think; once I learn them, they push my design process" CS2-012.

2. Pushing boundaries. Over half of the participants express that if they could do the task again, they would design such that they push the limits of the robot further (i.e. more curvy curves, push more, less constraints between curves, etc.). The robot is then encouraging them to be more experimental, getting out of the safe area of their designs.

3. Understanding of machine capabilities, robot coordinates and motions.

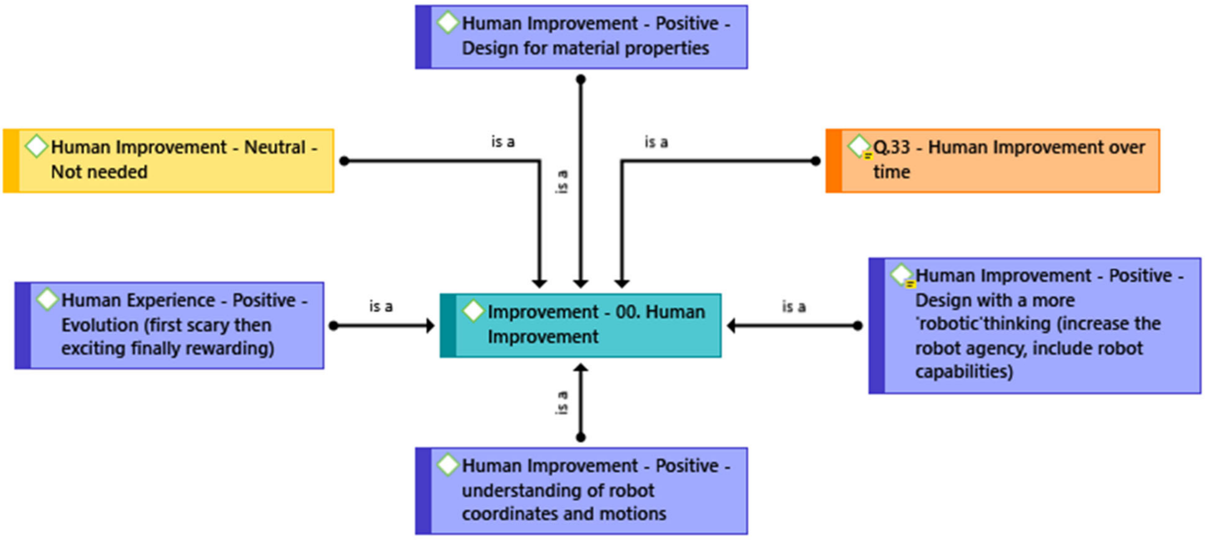


Figure 9-10 Main human improvement topics as covered by participants.

Robot improvement

In this case study the robot is not learning nor adapting; the improvement of the team performance is solely driven by the human. However, participants rated the team improvement high with comments like *"using the robot made me feel highly empowered when it was doing what I asked him".*

An additional measure was applied to understand participants' perception of improvements in the development of the task caused by the robot. Considering that the improvement of the team in this task is solely from human input, this was called the 'human improvement' contribution to the overall team's performance. Subtracting then the human improvement from the improvement of the team, as measured in the team improvement indicator, we obtain the 'robot improvement' contribution to the team's improvement. The literature suggests this as a successful method to understand the relative contribution of the team members to improvement over time in cases where the robot is not learning nor adapting (Hoffman and Breazeal 2010). The combined robot improvement had an average of M=4.2.

Improvement summary

The results indicate that the human and the robot improvement rates are partly matching. Even in the cases when participants score the improvement of the robot very low, they then go to give a high score to the team improvement and to the robot' s contributions to the task. When the scores are paired to eliminate any bias, two scores make for a higher improvement rate for the robot.

9.2.4 Robustness

Robustness is a measure related to the task and to the division of labour for team members in the task.   Five quantitative and qualitative tenets were evaluated under this category and are considered fundamental for the functioning of the design HIRC team are: reliance, shared identity, responsibility, attribution of credit and attribution of blame.

Reliance

Reliance was measured from the reaction of the participants in those ambiguous situations in which the robot had better information than the participants, and they could decide whether to solicit input from the robot or not (i.e. after each scan the robot would possess better knowledge about the material deformation). Through revising the videos and field notes it became clear that some participants would check the digital information from the robot scan but would decide to manually jog the robot for plunging rather than allowing the robot to perform the plunging path it was suggesting. These cases were considered as reliance on the digital information but not on the robot.

Reliance on the digital information was generally high. Only three participants did not care to use it and decided to do the plunging based on their own intuition. The rest of the participants were divided as follows:

- **Reliance on the digital information but low reliance on the robot.** Nine participants decided to manually jog the robot for plunging while consulting the digital information on the screen, rotating the digital model and continuously checking that they were plunging in the positions suggested by the robot.

- **Mixed human–robot reliance.** Four participants allowed the robot to automatically plunge in the suggested positions on some iterations while doing some iterations manually jogging the robot to plunge either to *'refine'* some areas or to *'experiment'* with new things.
- **High robot reliance.** Nine participants allowed for all their scanning and plunging iterations to be done by the robot automatically.

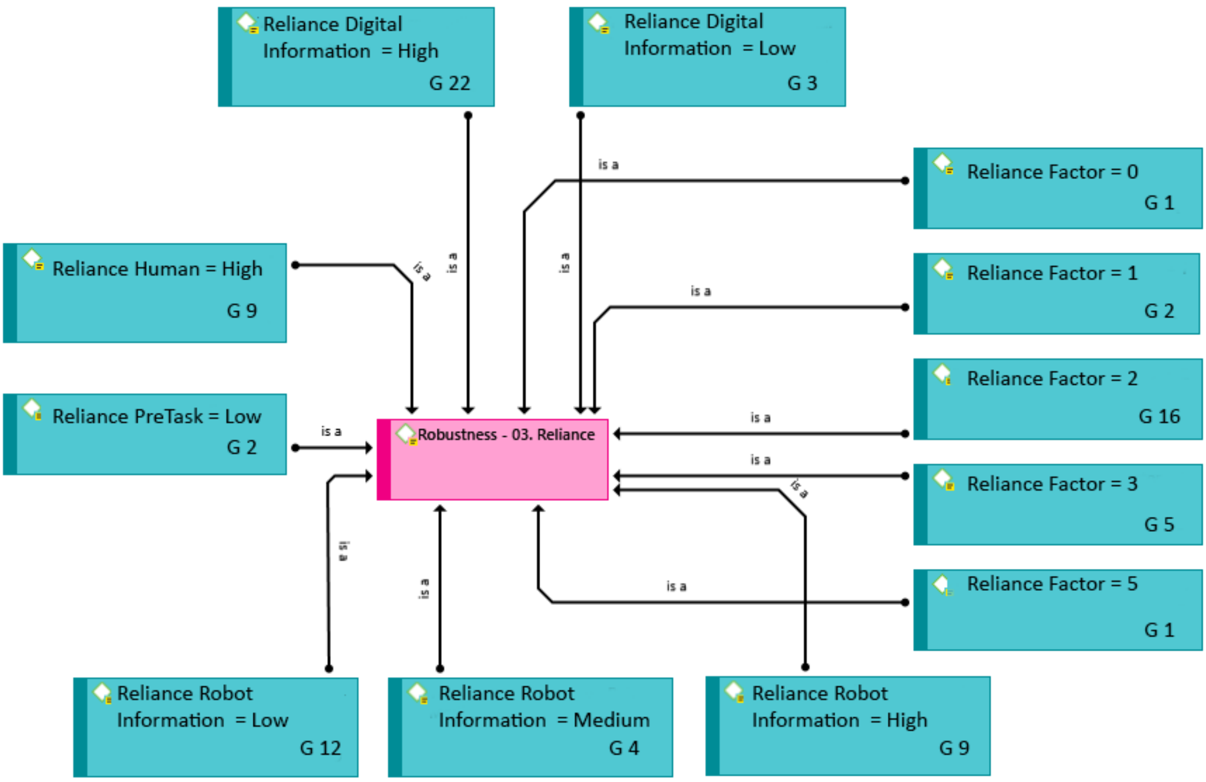


Figure 9-11 Degrees of reliance and reliance factor in the HIRC team. G indicates number of participants under each field.

A reliance factor was established which indicates the number of scans each participant performed. Most participants (16) performed two scans, with only one participant not doing any and one participant taking five scans. Plunging iterations will usually be one more than the number of scans taken. Figure 9-11 shows the different degrees of reliance (robot and digital information) and the number of scans taken by each participant, indicated as reliance factor.

During the first session two participants indicated they would be more interested in manually jogging and experimenting with the robot rather than doing rigorous form-finding with it. This is indicated as low reliance pre-task. They did not change their minds and manually jogged the robot in all their iterations. However, they did become curious about the material deformations that were happening and scanned to compare differences between the different stages of their physical models.

Additionally, participants would have different reactions to the scans (Figure 9-12). For example, doing manual plunging after scan one, then allowing the robot to do the plunging automatically after scan two, and finally doing a manual plunging iteration after scan three.

By the end of the exercise 18 plunging iterations had been done with participants holding the teach pendant but running the program generated by the robot; eight plunging iterations in automatic mode; 22 plunging iterations done by manually jogging the robot. All participants used some combination of this (i.e. one manual, one robot program, one auto etc.).

Shared identity

Shared Identity has been coded in the interviews by counting the number of times that the participants use collective language against those when they use individualistic language to refer to the development and results of the task. The rationale is that if participants feel closer to the robot, he or she will refer to their work during the task together as that of a team and use collective language to describe it such as us, we and ours. If the participant feels that the robot is not similar to himself or herself and is only a tool used during the process, he or she will describe the task using individualistic language such as I, my, mine (Hinds et al. 2004; Kim and Hinds 2006).

During their personal accounts of the task participants used collective language 48 times and individualistic language 31 times. The words considered for this are:

1) We: 48 mentions

2) My: 31 mentions

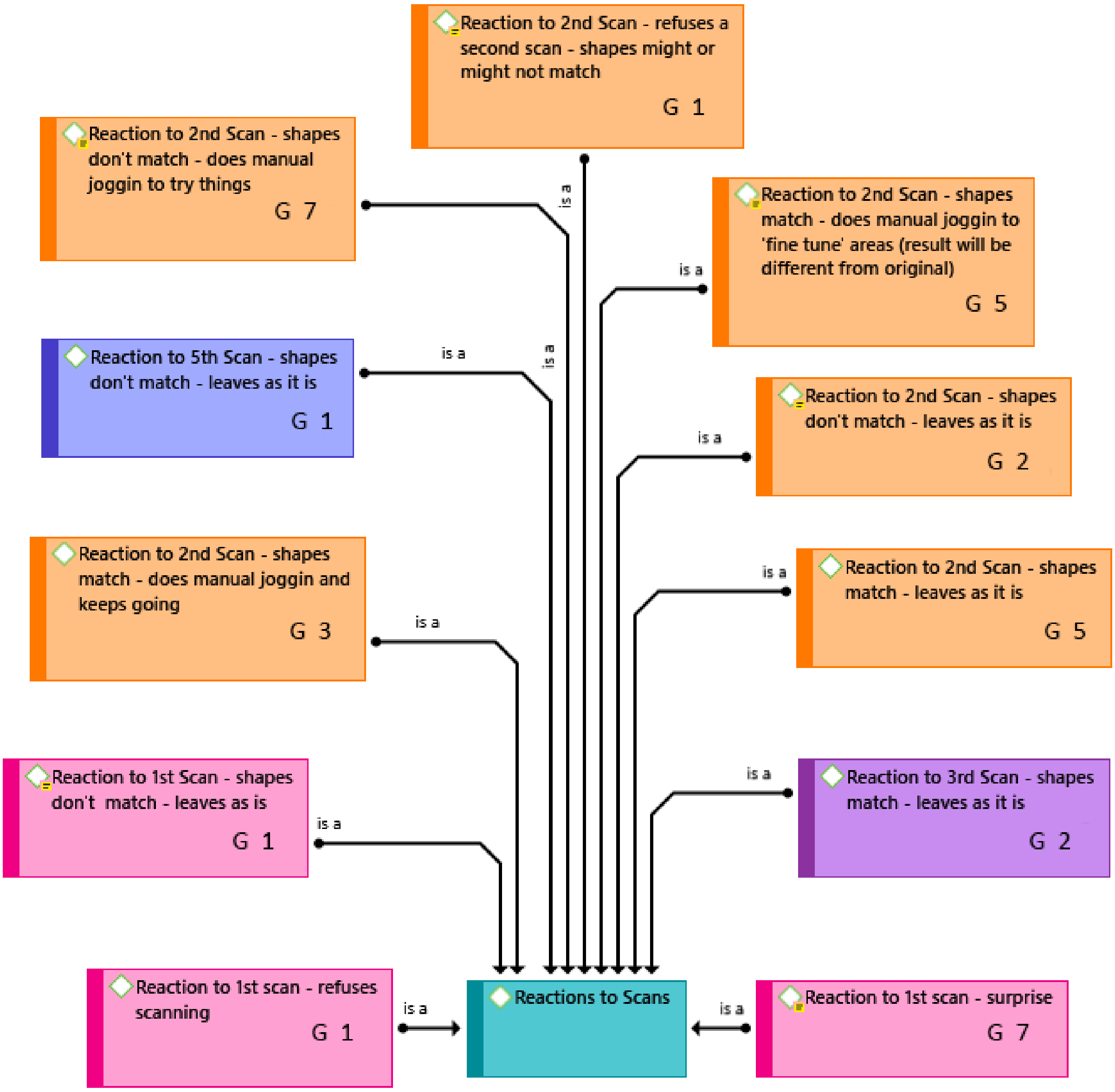


Figure 9-12 Actions taken by the participants after each scan and the reason for the reaction. The letter G indicates the number of participants that took each action.

As the task evolved participants' relationship with the robot also changed. Five participants, who during the second session expressed their intention to manually jog the robot after receiving feedback but not using the robot to do the deformation by itself, end up describing the task as a collaborative endeavour (i.e. using 'we').

Two other nonverbal indicators of common ground between participants and the robot were used to measure shared identity: the extent to which participants appeared engaged with the task (i.e. testing new things vs just doing the basic requirements) and the proximity of the participants to the robot.

The engagement with the task can be considered high, with only five participants limiting themselves to doing the task and not engaging further with the robot nor the researcher (i.e. asking questions, playing with the robot, moving around, etc.).
Proximity to the robot was an evolving variable; as the task progressed participants became more comfortable with the robot and their proximity to it increased. During the second session 13 participants approached the robot while 12 remained at the edge of the cage. By the third session only one participant remained at the edge of the cage and generally appeared uncomfortable when jogging or approaching the robot.

Responsibility

Responsibility has been coded directly and indirectly from questions in the questionnaire (Figure 9-13). The hypothesis being that people who rely more on the robot partner would feel less responsible for the task or would feel a shared of sense of responsibility (Hinds et al. 2004; Pellegrinelli et al. 2016a). Additionally, in the context of this task a higher sense of responsibility indicates that the participants perceive the robot more as a subordinate than as a peer. Interviews were also coded for instances when participants spoke about the robot as a tool. This implies that they see it as a pen or hammer that serves a purpose but cannot be held responsible for its actions.

Participants' sense of responsibility over the task was low with (M=3.8, SD=1.6); their sense of ownership was somehow higher (M=4.8, SD=1.5), whereas the responsibility they attribute to the robot over the task, mainly the errors, was the highest (M=5.0, SD=1.8). At some moment during the interviews one third of the participants expressed views indicating they viewed the robot as a tool.

“You're the designer and you're using it as a tool” CS2-001.

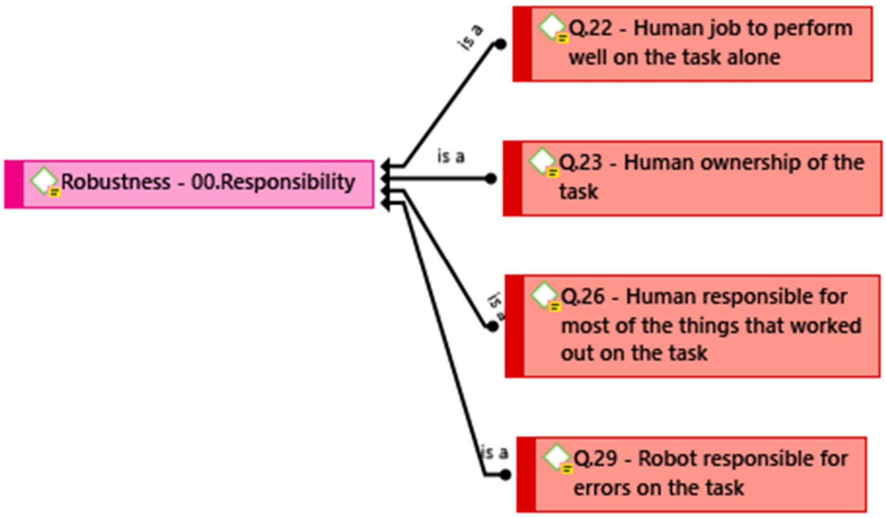


Figure 9-13 Question in the post-task survey that evaluate responsibility.

The results differ from the literature in which people had been shown to feel most responsible for the task when collaborating with machine-like robots (Hinds et al. 2004; Rau et al. 2010). This might have been influenced by the robot being presented as a partner for the task and the constant feedback and suggestions offered by it during the research task. Participants unhappy about their results hold the robot responsible for the task. This will be further discussed with the constructs related to attribution of blame and its relationship to responsibility.

Attribution of credit & blame

“If it’s someone else’s fault you don’t really own it” (Chollet 2018).

Attribution of credit and attribution of blame were measured as indirect indicators of responsibility. They measure to what extent people attribute credit or blame to their partner (robot). Blame is not equivalent to the abdication of responsibility. However, people who feel more responsible for the task are less likely to blame their partner for the errors (Goodnow 1996). When the questions refer to the credit that the participant attributes to himself or herself (human) the answers are reverse scored.

The patterns of attribution of credit and attribution of blame are consistent with the literature (Ross 1977; Broadbent et al. 2011). Attribution of blame to the robot was higher (M=5.5, SD=1.6) than attribution of credit (M=4.2, SD=1.6). There were not any significant differences between the attributions of credit and blame by female or male participants

Attribution of credit and blame became an interesting construct. The majority of participants credited the robot for its contribution to the task or remained neutral about how much credit the robot should be getting, whereas only one participant directly attributed blame to the robot for his design. Participants would tend to attribute blame to themselves and absolve the robot from any blame. Phrases such as *"the robot did its part of the contract perfectly; it was me who messed up"* or *"the problem with machines is that they do exactly what they are told and we told it the wrong things"* were common. The main situations that caused participants to blame the robot are:

1. It pushed too hard, causing the material to tear hence changing the design results (this was irreparable).
2. It did not cut as expected, missing some parts of the pattern (in these situations the cut could be repeated with the missed areas).

Robustness summary

Robustness analysis indicates a strong reliance on the robot arm, both on its actions and on the information, it was providing as well as the paths suggestions it generated. The participants in this study were young and well-motivated to participate which could influence their disposition to accept the suggestions made by the technology. Their initial reactions to the robot arm were positive and of excitement. Words to describe it go from *"cool"*, *"exciting"*, and a *"new toy"* to *"adorable"* and *"I love talking to him"*. Participants generally felt comfortable with the robot, working next to it, jogging it and moving it around. They were talkative with the robot. Engagement with the task and designs was high. Participants would describe feeling empowered by being able to relate to and work with the robot.

Although reliance on the robot was high, designers like to be in control. In most cases, especially if the digital and physical shapes were matching after the robot's automatic plunging, participants would want to manually jog the robot to "*refine*" areas, knowing that now the shapes would be different from their original design. This suggests that although they are willing to cede agency to the robot, designers like to have the final word. Additionally, literature suggests that in tasks where little risk is involved participants tend to have higher reliance on the robot partner. During the interviews participants mention that allowing the robot to do the plunging (reliance) allows them to concentrate on the bigger picture and on refining their design intent. Reliance in the robot during the design process is positive and beneficial.

Participants were mostly happy to follow the robot's advice; even when they were jogging it manually, they would look for the scan to check where to do the plunging. A possible explanation for this effect is that the task was relatively straightforward, even with the ambiguities, it did not allow the robot to display a high level of skill or competence. A situation including machine learning in which the robot has substantially more skills and knowledge relative to the participant may reveal different effects as participants might feel overwhelmed by the robot's knowledge. In this case robot and participant could understand the material deformations to a considerable degree.

For the context of this research, it was important to disentangle reliance on the digital information from reliance on the robot. Participants will trust the information and try to inform themselves by it but would not trust the robot in equal measure. An explanation may be that designers have a longer story of relating and working with computer-aided design systems than with robots (Loukissas 2012; Yagoda and Gillan 2012; Joe et al. 2015).

Participants felt a common ground between them and the robot; this was understood mainly by their use of common language to describe the task. Additional nonverbal indicators (proximity and engagement) did not provide any significant differences. This is consistent with the literature (Hinds et al. 2004) and these variables may be discriminated in further studies.

Responsibility for the task was shared: participants did not report feeling extremely responsible for it. This indicated that they were willing to cede agency to a machine-like robot. However, the literature suggests that those people feeling more responsible for the task are willing to explore more options and are more active about finding appropriate solutions, hence mishaps are avoided (Parasuraman et al. 1993; Hinds et al. 2004). The over-reliance on the robot may be due to the young age of the participants and willingness to work with it. However, it may have also resulted from trusting the robot without double-checking external variables (i.e. frame height, etc.) resulting in the robot damaging the material and hence higher levels of attribution of blame. Additionally, participants were not able to detect the situations in which the robot was not equipped to perform due to environment changes (i.e. frame movements) resulting in poor robot performance. Participants with a high sense of responsibility would have worked to figure out how to handle these changes in order to enable the robot to proceed towards the objective (Parasuraman et al. 1993; Hinds et al. 2004).

Consistent with the literature, reliance and responsibility were not strongly correlated. However, responsibility is associated with more attribution of credit and blame. People feeling less responsible for the task attribute more credit and blame to others (Hinds et al. 2004; Kim and Hinds 2006). Participants would blame the robot for the errors as much as they would blame themselves. They will credit the robot with actions beyond the ones directly related to the task, such as allowing them to see the bigger picture, gaining insights into their design process and enhancing their perceptions through the more detailed or unexpected information than what they could perceive with their eyes. It is important to note that this study was conducted with one robot and one human partner working together at a time. It would be interesting to know the results when the team is bigger with more participants. Would a single team member distribute the blame between all other team members or attribute most of the blame to the robot?

9.3 Word2vec Analysis of Interview Data

The findings from the interviews and anecdotal evidence were tested using a *word2vec* (Mikolov et al. 2013) neural network trained on the corpus of participant interviews. The data was cleaned to remove joining words. All words with a word count below three were removed as they could cause noise to the classifier.

word2vec (Mikolov et al. 2013) is an unsupervised learning method that uses a neural network to capture relationships between language elements and their context. It generates a distributed representation of words and phrases in a shared high-dimensional vector space. More specifically it learns to predict neighbours within a given text window for each word in the vocabulary. w*ord2vec* captures the syntactic and semantic relationships between words and phrases.

The following hyper-parameters were tested:
Dimensionality of the feature vector = 4,
The maximum size between analysed words within a sentence = 8,
Ignores all words with a total frequency lower than 2 in the corpus,
The model was trained for six epochs using a stochastic gradient descent with a starting learning rate of 0.25 that linearly declined to 0.001.

Table 9-1 shows the results from testing the model to find five more similar words individually to “robot”, “design”, “weaknesses” and “strengths”.

Table 9-1 Word2vec 5 words more similar to robot, design, weaknesses and strengths

robot	idea	think		designing	like	trust
design	with	robot		doing	think	like
weaknesses	takes	different		confusing	tool	model
strengths	helpful	different		strength	think	experience

The model was then queried for all the words related to robot as a partner in the design process by getting five more similar words to the positive words [“robot”, “weaknesses” and “strengths”] and less similar to the negative word [“tool”] (Table 9-2).

Table 9-2 Five words more similar to robot, weaknesses and strengths which are less similar to the negative word tool.

Positive = [“robot”, “weaknesses”, “strengths”] **Negative =** [“tool”]	reliable	helpful	good	strength	different

The model found a similarity of 0.998 between the words *“robot”* and *“trust”*. Suggesting that both words are closely related in participants’ accounts. To test the reliability of the model pairs of identical words were tested and it gave a similarity of 1.0.

Finally, from the four words *“robot”*, *“design”*, *“partner”* and *“concrete*” the model was asked to find the *odd word = “concrete”* suggesting that robot, design and partner are closer in the interview corpus than the concrete material.

Figures (9-14) and (9-15) show the words sized by frequency during the interviews.

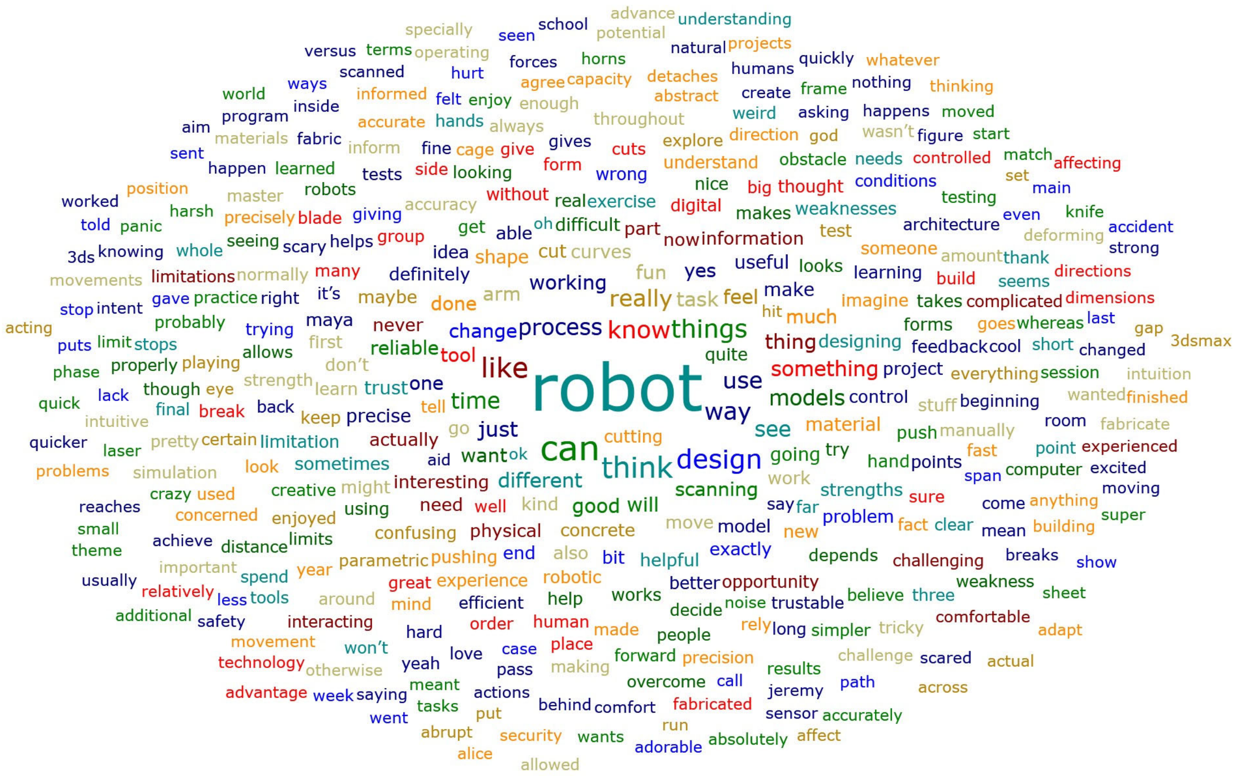


Figure 9-14 Word cloud representation of frequencies on interview data.

Figure 9-15 Frequencies of interview data in descending order.

9.4 Additional Indicators

Two additional indicators were considered: positive vs negative constructs and the designers' engagement with the design task

9.4.1 Positive vs Negative

Across all the evaluation parameters, including themes and sub-themes, 56 negative feelings and 90 positive feelings were expressed. This variable is counting the number of different items that the participants describe as positive from the task, interaction with the robot, robot elements, human elements and comparing them with the number of negative elements that participants find from the same.

9.4.2 Level of Engagement

An initial hypothesis was that the greater the human teammate's personal investment in the team's goal, the lower his or her threshold for violations of expectations (Groom and Nass 2007). The research task is evaluated to find if cases in which the designer spent time working through all the challenges of the design exercise resulted in he or she giving less or more agency to the robot and being less willing to accept any errors made by it. This was compared to cases where the designers had asked the researcher to make a design based on a simple sketch they made.

Quantitatively there were no significant differences in the perception of team fluency between both groups; neither in the attribution of credit nor blame to the robot partner. During the design task both groups spent equal amounts of time working with the robot and refining their plunging iterations. The average time spent on the design exercise is 75 minutes, with 45 minutes being the quickest time and 95 minutes the longest. The interest and engagement in the collaborative form-finding exercise seems independent from the time spent in developing the design.

9.5 Possible Source of Errors

Possible sources of errors to be considered during the design and data collection process are:

1. Bias by the researcher being present during the experiment. The *'Hawthorne effect'*, is concerned with the presence of the researcher during the experiment and how the simple act of the participant being part of an experiment influences its behaviour. It has been the subject of considerable debate amongst researchers and scientists in HCI. There has not been enough proof of the size of this effect, the conditions under which it operates or its mechanisms (Kolata 1998; Macefield 2007; Lazar et al. 2010; McCambridge et al. 2014) and remains a highly controversial topic. Parsons in his 1974 reinterpretation of the Hawthorne effect (Parsons 1974) concludes that it is not the act of being observed or of the researcher being present which influences the participant's behaviour, but the constant feedback that they get of their performance while participating in the experiment (Macefield 2007). The research exercise was conducted with the following considerations, based on Mayo (1933) and Parsons (1974):

- Pre-task interviews were conducted to ensure that the combination of user, task and system was always novel.
- The relationship between the researcher and the participants was kept neutral. Participants did not have any reason to impress the researcher; their participation did not have influence on any class, grade or their regular activities in the university.
- Participants did not receive any performance feedback during the duration of the design exercise. Interactions were kept to technical problems with the interface, material and robot. Data has not been made available to the participants.
- Participants were made aware that the main objective of the case study was to understand the relationships enabled by the robot between designers and materials through the design process rather than evaluating their performance.

2. How accurately the task scenario mirrors a real context. Using robots to achieve a human task involves the interaction of two complex systems. One system is of higher complexity: the human, including human intelligence, motivation and skills. The other is a digital processing system with a physical, mechanical arm and its kinematic solvers of lower, but still substantial complexity (Wolf et al. 1989). Predicting the results of this combination of complexities is very difficult or almost impossible. Due to this scenario and a high dependence on details during the interactions of these complex systems, HCI research in natural settings tends to be very noisy; the proposed laboratory context aims to reduce some of this noise while providing more control. Wolf et al. (1989)report very few instances of dramatic differences between lab tests and real world uses. Moreover, they point to lab experimentation in HCI as strategic *"in the elucidation of human cognitive needs as a step in the invention or definition of new kinds of systems or modes of system application"* (Wolf et al. 1989, p.267).

3. Do study participants provide a representative sample of the target user group? The aim of this research is to understand key human elements relevant to HIRC in design tasks. The robot in the task is a partner to assist non-expert robot users, architectural designers in achieving design goals. The task considered a prototypical holistic design process that included material, fabrication and form-finding. A pre-task interview was conducted to ensure that participants represent the target group.

4. **Participants not telling "true" stories during the interviews**. Participants may have over-emphasised their relationship with the robot arm, as they were being asked many questions about it. Additionally, the novelty of the tool and of working with it may have changed how they spoke about themselves resulting in conversations that were not typical of their experiences. Questions were asked from many different angles and interview transcripts were triangulated with questionnaire answers, field notes and performance behaviour. Participants were proud and eager to talk about their design process and their interactions with the robotic manipulator. In general, regardless of individual challenges, they described satisfaction with the task. Through the evaluations, cross-referencing and interactions there is a level of confidence

that participants were not telling purposeful untruths. However, it is important to note that participants' accounts of their experiences are only accounts embedded in the moment of the conversation, after the design task. They may not be described in an identical way if asked again. These accounts encapsulate the way the participants felt after an intense form-finding physical and digital design exercise conducted with a robot and that resulted in a physical object which they might have liked or disliked. Different challenges were encountered by the different participants which would have influenced how they remember and think about the events, but not the events themselves.

9.6 Team Fluency Findings Summary

> *"Robots and other machines can control, precision and power the designer relationship with the material and his design. This relationship changes once the material manipulation doesn't depend on hands' abilities anymore, but our capability of thinking the design and programming the machines properly*" CS1-008.

Team fluency is crucial for collaborative human–robot teams to exist. Robot's actions need to be perceived as fluent by their human partner in order for robots to be accepted as collaborators and productive members of a human–robot team. However, fluency in non-repetitive, non-practised tasks has very different implications. Humans would not be expecting coordinated physical interactions as they would on repetitive tasks (Hoffman and Breazeal 2007) but they would be expecting understanding and ease of intellectual communication, including design intent and steps towards its realisation. These qualities are observed in a variety of human behaviours but are virtually absent in human–robot collaboration.

Designing with the robot arm represents a new form of interaction, which diverts from traditional design methodologies where the human is in absolute control of the task completion. In a human-only situation, humans can use their senses to adjust to any deviations and execute the task; with a robot in the loop the designer is practically removed from the physical task execution and is required to monitor the robot's performance and the material's performance and bridge between both. Giving up control is a difficult task without trust and understanding of the other agents. Additionally, unlike software automated design, robots are mobile and have a degree of anthropomorphism which introduces an uncertainty not found in design software. However, using the robot and allowing some distance between designers and their design process proved beneficial as it allowed designers to constantly zoom out and see the overall picture.

A level of design maturity is required for participants to cede agency to the robot partner. Younger architectural students may not have enough control over their design process in order to be able to include other agencies in it. Additionally, an interest in the genesis of the design and its quantifiable parts is required. Students in their earlier years have not conceptualised their design process to a stage where the quantitative information provided by the robot is useful or relevant.

The focus of this case study was on robots working as design partners, although conducted in a controlled laboratory setting. Realistic aspects of the design task were intentionally designed like form-finding a shell structure, working within the constraints of the material and using the appropriate software tools. Participants were free to interact and talk with their colleagues about the work they were doing and get design feedback from other sources. The rationale is that people's responses to robots in the design studio will be significantly influenced by the social and organisational context around them (Siino and Hinds 2004).

The robot used for this study is an industrial robot arm which is nowhere near as human-like or intelligent as more advanced and autonomous robots can be. This had an impact on reliance which is weaker than in studies using more advanced, smarter robots. Additionally, the task did not require advanced human-like behaviours. It is anticipated that as more intelligent behaviours are introduced into the robot and it gives stronger advice over the design task, including benefits and preference on one set of actions over another, the human reliance will differ and the robustness of the team will be challenged in different ways.

In open questions, participants would attribute more human qualities to the robot such as gender, intelligence, emotional preferences, as well as credit for success than in questionnaire answers. Interestingly, there is also a tendency towards self-deprecation from the participants in regard to their performance during the task. A high number of participants feel the robot did its part of the contract correctly whereas they messed it up. This poses an interesting challenge going forward, when considering robots that can learn, adapt, and which might have detrimental effects to human self-confidence and trust. The adverse effects of robot performance on the human intellect have not been sufficiently addressed by the literature. Additionally, more intelligent and autonomous robots (i.e. able to solve problems, choose between alternatives) would be less obedient. Designers like to be in control, although participants acknowledged that ceding some control over to the robot yielded better results, the control and decision-making was always with the human. It was never a question of giving it to the robot. Further research is needed to understand design team fluency with smarter robots. However, the results from this research urge future research to consider a HRIC design workflow that strives to keep a balance between the team members (i.e. a very smart robot can result in humans becoming disheartened).

The expectations that designers have about robots and their experiences with them are another factor that will have a strong influence on the HIRC design process. As designers gain experience, the novelty of the technology wears off and designers would develop and find ways to adapt the robot so it better fits their design needs (Barley 1986; Orlikowski 2000; Hinds et al. 2004). Two participants had previous experience with robots, but in a very limited capacity which cannot be considered enough to allow them to establish clear expectations about the capabilities of a specific robot arm and less about the capabilities of robots in general. Designers who better understand the robot’s capabilities will design to exploit those abilities. Collaboration will be affected by the gain in experience. The findings show that after three sessions an increased understanding developed in participants who were eager to incorporate a more *‘robotic thinking’* to their design and could see design gains by doing so.
Participants in this task were reasonably motivated to participate. The emotional response to

the robot includes words *"amazing", "cool"*, *"empowering to use"*, *"fascinating, it comes alive".* Further research is needed to understand the relationship between the robot, the task, and the willingness to rely on the robot for designers with different attitudes towards technology.

A number of metrics, specifically the ones related to the team's improvement over time, the robot's contribution to the task, and the trust in the robot, show significant differences between the questionnaire answers and the answers during the interviews. The qualitative answers of the participants are more favourable than the quantitative scores given to the robot's performance. Positive comments go from "*highly surprised and impressed with the robot's performance"*, surprise that the robot *"knows"* where to push the fabric to achieve the desired shape and even more surprise that it can match digital and physical forms. Participants claim they connected with the robot going as far as saying it *"Is like this third hand*" (CS2-003). In terms of the robot's contribution and team improvement over time, participants remarked how they adapted and as the task progressed, they felt the robot was empowering them to do more. Comments included *"First it was a little scary for me, then it became really exciting and rewarding"* (CS2-003), *"it increased my reach, possibilities and vision, and my enthusiasm"* (CS2-019). One went so far as to claim that *"by the end of the session, we were good friends, the robot was understanding me, now I feel that I love him".*

Chapter 10 DISCUSSION AND CONCLUSIONS

10.1 Introduction

The most interesting collaborative systems are those producing emergent results, that are genuinely unexpected and rich, and which could not have been predicted as an output of the constituent parts. The relationship between the input parameters and the output for these systems is generally complex and non-linear and there is a sensitive dependence on the initial conditions. In many systems, the most interesting emergent behaviour occurs close to the boundary between regularity and chaos (MacKenzie 2013).

The existing literature enhances our understanding of the development of team fluency factors when humans interact with robots; however, the context is different. In a military or industrial human−robot teaming, the functions of both agents are very different from those in a design scenario. Human−robot team fluency development in design tasks is influenced by other context-related factors. This section discusses the findings to answer what are the key digital, mental, and physical factors that enable designers to transfer agency to the robot during the design process. It identifies some limitations, as would be expected from any research. However, these limitations provide exciting areas of exploration for future work and to enhance the understanding of the influence of human factors in HIRC during the design task.

10.2 Discussion

Based on the literature review carried out, four main constructs were defined to evaluate team fluency in HIRC in design tasks. To identify whether they were enablers or barriers and their relevance to the design task, an exploratory HIRC case study and a main case study of a collaborative form-finding design exercise were set up. Qualitative and quantitative data from 31 individuals were collected and analysed by using template analysis, atlas.ti, and SPSS. A number of key enablers and barriers emerged:

The first aspect to be considered is the need to translate design thoughts in a way that can be understood by the robot. Teammates expect their robot partner to provide coordinated, dynamic behaviour that engages with their own. In a repetitive task, like those related to manufacturing, we can expect the human and robot behaviours to become increasingly coordinated as the task is repeated. The design activity is an intellectual activity; designers want to communicate their intent to the robot arm, including their preferred way to execute it. Debate on this issue is something not found in the literature.

Working with the robot gave participants the freedom to design unexpected things but also forced them to work within a new set of constraints (e.g. robot joint limits, singularities, movement range, etc.). These constraints were seen as a limit for some but as an opportunity for most. Almost all the participants discussed the constraints as opportunities to leave the endless possibilities of the digital world and explore a real physical environment mediated by a precise machine. It became crucial to incorporate machine thinking into design thinking to take advantage of the properties of the material and machine. Once the machine is understood, the design possibilities increase. Robot motions are a result of the robot kinematic behaviour. Because of the number of axes (6) that the robot has, this results in a multi-dimensional space that cannot be intuitively described. In addition to the robot´s movements, the sequence in which they are performed is critical for the success of the collaborative design process. Tools are continuously being designed to aid designers in robotic motion planning tasks that enable smoother relationships between the robot kinematics, the path sequence, and the design software (e.g. machina (García del Castillo y López 2019)). As these tools enter the architecture repertoire exploring the multi-dimensional design space that includes material, design, and robot motion planning should become more accessible to designers.

As designers become comfortable using 3D printers and other fabrication machines, which do not require material or machinic understanding, the gap between designers and fabrication methods becomes larger. The premise from participants that if they were to do it with their hands, it would be more accurate because they know exactly what they want is also false. Unlike in the case of craft processes, architects cannot mould a building to their preference or desires with their hands. There is an inherent urgency to learn how to translate design thinking into machine operations. Mumford (1967, p.39) describes this as order and creativity being complementary *"he has to internalize order to be able to give external form to his creativity"*. The robot as a design partner from the early stages would allow an understanding of the implications that small design decisions have downstream the production process and help designers externalise their design processes in a systematic way. On the basis of the research results, introducing RAD workflows from the early stages of architectural education would prove beneficial. It will expose the importance of a design that engages with the physical in a quantifiable way by offering feedback and becoming instrumental during the exploration and understanding of the design space. The robot, as a design partner, offers a middle ground between unlimited freedom and restricted fabrication.

The design process is a complex task because of its proprietary nature and that of the resulting designs (Tsigkari et al. 2013). Designers develop their own intuition and approach to deal with the different variables presented and reach a satisfactory, although not a single, solution. This leads to the question of ceding agency to the robot. Participants are naturally interested in machines and digital techniques and technologies, irrespective of their year of study or work experience. They are keen to give agency to the robot and allow it to do its part of the task. Furthermore, they want to incorporate features in their design that allow for increased robot agency and reduce their control. However, once the robot achieves the design goal, even if participants are initially satisfied, they make a final round of manually jogging the robot and manipulating the shape to fine-tune or emphasise some areas. Participants who run the robot program in manual mode would also stop it to do their own massaging before allowing the program to keep running. It can be said that the robot provides the overall logic, and participants are providing the fine-tuning they consider necessary as part of their exploration process. This interrelation between the robot analysing the form and doing most of the shaping with the participants' fine-tuning of some areas can be described as a human–machine collaborative form-finding process. However, "*designers like to always be in control"*, working with the robot forces designers to give up some control in order to obtain better results. The literature concurs that humans enjoy ‘doing’ and ‘deciding’ by being involved in the process (Billings 1991; Fischer 1995). As we enhance ourselves, we reduce ourselves by giving away part of the agency and hence, ability to control the world (Faggella 2013). For robots to progress and become partners in the design process, designers need to be willing to relinquish more control – through programming – to them.

The second aspect, which does not appear in HRC literature, is the engagement with the software, coding, and robot path planning aspects of the task. Traditionally, the digital programming of the task is considered as done by someone else and measured as the trust in the ‘robot programmer’; participants are conscious that *“they are not trusting the robot but the person who set it up”* (Charalambous 2014, p.149). The collaboration in a design scenario is not limited to the physical aspects. Designers have to relate their design thinking to the robot’s physical and digital capabilities in order to be successful during the exploration. Furthermore, the design thinking changes and evolves with the exploration process, making it a dynamic construct. The complexity or opaqueness of the robot software and interface can affect their overall perception of the robot as a partner. If they find it difficult to communicate their intellectual intentions to the robotic partner, they might see the robot as an obstacle rather than a collaborator in achieving the task, decreasing trust, even if the physical communication is clear.

An interesting finding is that engagement with the digital aspects of the robot does not mean engagement with the physical robot (i.e. participants constantly asking questions about the robot’s digital workings but remaining at the edge of the cage when using it). At the same time, participants less engaged in the technicalities, who were initially considered to be less engaged with the task, spent more time jogging the robot, moving comfortably around it and at closer proximity to the arm. This is different from computer-aided design in which the engagement is purely digital and the dichotomy cannot occur. Additionally, the interest in the robot’s workings does not mean a shared identity with the robot, close proximity to it, and the existence of a common ground for collaboration.

A second point of discussion is the difference between the reliance on the robot and on the digital information. Participants' reliance on the digital information was consistent with the literature on HRI. Humans tend to trust and see automation as more reliable than humans (Dzindolet et al. 2003). Even in cases where the same information is provided by both humans and machines, humans will rely more on the automation. Literature places a strong emphasis on the relationship between automation reliability and reliance on HRC processes. As risk increases human reliance on the automation increases (Cosenzo et al. 2006). During the design process, designers are looking for answers rather than solutions. Although, the system is expected to be reliable and perform its tasks correctly, glitches and unexpected situations can be conducive to discoveries and better accepted than in an industrial setting. Reliability and reliance require from the system to perform as expected but also to have sufficient flexibility to encourage and enhance human exploration.

At the same time, it raises interesting questions for the organisation of a human–robot design team. For example: who has the authority to make certain decisions: robot, software, or human? Who has the authority to issue instructions or commands to the robot: software or human? It was clear that even in the cases when the participants decided to follow the software instructions, they would place themselves in-between the software and the robot by manually controlling and pressing the buttons in the teach pendant. Only in a minority of cases did the participants allow the software to directly instruct the robot. The answer might lie in a dynamic team structure where changes between the roles, responsibilities, and authorities are the norm. Designers will be inclined to allow the software and the robot to take the lead in one iteration and go to a human-led iteration thereafter. Agency is a continuously negotiated construct. Furthermore, it suggests that HRC in a design scenario is a three-agent problem, where the software as an intermediary between the human and the robot plays a role as important as that of the other two, but none of them takes precedence over the others (i.e. unlike in other three-agent problems such as NASA-distributed robot applications where the software is the third agent that coordinates both the human and the robot actions (Burghart and Steinfeld 2008)). This finding also appears to suggest a different approach regarding digital versus physical authorship. Designers would not have problems with the solution space presented by the physics solver engine, and the robot suggestions. However, the robot execution of the same suggestions proved problematic. Architects know that the fabrication authorship is shared (i.e. architects do not expect to build their creations themselves). Design authorship shared with digital tools and algorithms is also accepted. However, physical design processes offer a different set of intellectual perceptions which make designers less willing to share the credit with a machine.

The third discussion point centres on the robot's performance as a network of its different actants: robot body, software, end effector, and feedback, and its implications on trust (Broadbent et al. 2011; van den Brule et al. 2014). Hancock et al. (2011) in their meta-analysis of human–robot factors classified the reliability of the robot performance as having the highest impact on human perception. This was reconfirmed by the work of Charalambous and van de Brule (Hancock et al. 2011a; van den Brule et al. 2014; Charalambous et al. 2016), which highlight how the robot's performance on the task influences human behaviour. An unreliable robot will eventually decrease its human acceptance. What is important to consider is that the robot system includes the reliability of the end effector. Designers make a specific differentiation between both. This is of particular relevance to design HIRC. Robot arms have been perfected in their design through the years together with industrial end effectors, such as grippers, welding and painting guns, etc. However, designers are constantly making new, untested end effectors, and a decrease in their reliability will not affect the human trust in the robotic partner.

The next discussion point revolves around the robot's characteristics. Its motions were a positive factor in the participants' perception of it. Most designers felt reassured that the robot does not move from the ground. The motions are very controlled but emotionally described as *"the robot becoming alive".* There is a gulf between the human's rational and instinctive reactions to machines. Participants know that the robot – particularly in this case with an industrial robot – is nothing more than a programmed automaton made of huge parts of metal

(Gannon 2018). However, describing it as a live creature or how it goes from dead to live when it starts to move is something recurrent. A possible factor influencing the human attributes of liveliness to the robot is the human *"like-me"* perception of the robot (Hoffman and Breazeal 2010) and the tendency to anthropomorphise even simple interactions by assigning them intentionality. This becomes particularly relevant when objects, including robots, are in motion (Saerbeck and Bartneck 2010).

The physical attributes of the robot received little attention from the participants with most of them describing having a big robot as encouraging and empowering. This opposite to the literature which suggests that smaller robots increase trust. The robot's appearance did not seem to be a factor contributing to how designers felt about the robot. The literature provides contradicting results with some research suggesting that robots should not be too human in appearance, while others suggest that a more human-like appearance will make them more engaging to people (Bartneck et al. 2009a; Broadbent et al. 2009; Rau et al. 2010). Constant to both cases, anthropomorphic and tecnomorphic robots, is that the robot's appearance should match its abilities so that no unrealistic expectations are generated in the human user, which might harm the relationship later when they are not met (Bartneck et al. 2009b). A possible explanation is that designers perceive the industrial robot as a tool designed to complete a task; hence, its appearance is not important. Humanoid features might enhance unrealistic expectations. Additionally, a humanoid robot might be able to take more responsibility, credit, and blame over the task.

At the same time, lack of behaviour legibility was a cause of concern for most participants who desired the robot to indicate its next actions. As humans take cues from other humans and know how to collaborate with them, similar protocols for human–robot collaboration are expected. This is not a problem solely limited to industrial robots, as the same requests for legibility of the robot's actions and intentions have been found for self-driving cars (Dragan et al. 2013). Features to provide the human partner with an understanding of the robot intentions or indications about the robot next moves are also desirable for designers.

As the sessions progressed, participants felt more coordinated, comfortable and adapted to the robot. During the first session most of them were very uncomfortable to be inside the cage. This led to the first session having to be moved outside the cage after the first three participants. By the third session all the participants were freely moving around and interacting with the robot. The existing literature suggests that this bond takes time to form. Research findings suggest that it takes one or two interactions for designers to become comfortable with robots.

Finally, the robot feedback was embraced by the participants and was described as one of the best things provided by the robot. Participants from the third year and higher engaged further with the scanning process, performing it from different angles, and continuously comparing the physical and digital models; even if manually jogging the robot, they kept consulting the comparison by having the screen with the scan and the digital model up for reference. They felt that the continuous scanning and robot feedback helped them understand how the material deformed. A common reaction after scanning is the participant's surprise at how the shell is deforming compared to what they thought was happening. The non-linear behaviour of the material may be a contributor, as it was not something that the participants were expecting. Younger participants, were more inclined to follow their intuition and disregard the information given by the machine or consider it only to be a curiosity. A level of maturity seems to be needed in order to understand the feedback, have a positive attitude towards the machinic input, give some agency to others (humans or non-humans), and accept external comments over the design process which might differ from the designer's intuition.

Participants from the second year scanned an average of one time and participants from the third year an average of three, whereas older participants an average of five times. Note that half of the second-year participants allowed the robot to run the generated program rather than jogging it themselves. From this, we can derive that the difference is not about older versus younger students but is in the lack of experience and systemic thinking that makes them want to control the robot and the process themselves. The findings suggest the third year as a good moment to introduce a tool such as the robot arm to architecture design students. They have for the most part achieved a level of maturity in their design thinking and are starting to intellectualise their approach to design. They are keen on experimentation but want to have deeper insights into how and why things are happening. They appreciate the information given by the robot and acknowledge the value of feeding their design process and design decisions with quantitative information. Students who are more advanced in their design training or working graduates, although very interested in the feedback, are more settled into their design methods and feel that incorporating the robot into their design processes would require a steep learning curve which might set them back. Nonetheless, they are interested in learning and using it and can see the value of doing so.

Another interesting aspect of the feedback is the participants' perception that it allows them to see the bigger picture while providing them insights. A vision that they would not be able to get by themselves, as they are immersed in their design process. This is opposite to conventional wisdom and craft traditions which suggest that the closer your hands are to the material, the more tacit understanding you can gain. Material agency and material understanding during craft processes are related to the immediacy between the hand, the brain, and the material. These findings suggest that the material mediated through the machine can provide unnoticed perspectives, and the distance that the machine creates between the human and the material allows for the first one to change his or her focus from the detail to the larger picture and hence increase understanding while opening new and previously unforeseen avenues of exploration. The machine then becomes the environment in which the material and the designer communicate and understand each other.

10.3 ANT Interpretation

The human−robot case study for this thesis can be considered an appropriate paradigmatic example to understand collective agency (Poljanšek 2015). For Latour, following an ANT methodology means *"following the actors"* (Latour 1987). The question that guided this process was: what actants human, non-human, digital, material, immaterial are present in the data and how are these actants related and affecting each other from the designers' perspective? To answer this question, it was necessary to evaluate how the actants were conceptually tied together in the participants' language and whether they felt that the actants could relate positively or negatively to their overall design intentions.

Robots are normally considered to be a generic black box that generates actions to which people respond. An ANT perspective allows us to consider all the non-human actants that are part of the 'robot' but which generate diverse feelings and impressions in the participants. Problems with any of the actants would be blamed on the robot, and it is only during the interview that the participant will differentiate between the actant and the robot. Each of the actants that constitute the robot (colour, size, end effectors, software, material, frames, and tables) was examined and analysed as an independent agent that could influence the relationship between the human and the robot. In the particular case of a collaborative design exercise, designers are looking for partners that can support the process of discovery and inquiry. This is different from the traditional expectations of people collaborating with robots, which in general, are about the robot developing a specific task or supporting the human in solving a problem. Designers, through their creative process, want to understand all the actants: how to use them, and their limitations before any compromise to work with them is made. It is important to mention that as participants became more involved and knowledgeable about the robot, end effector, and material; their design possibilities became somehow reduced.

The five main avenues in which the adoption of ANT and its particularities helped in understanding of the design HIRC are as follows: 1) looking at the use of the robot and its components supporting the human design process as an evolving continuum characterised by the tensions between the actors involved; 2) as a process based on negotiations; and 3) as an emergent process with a relational nature. The use of ANT also helped in 4) facilitating the identification of the main actants constituting each of the relevant actors and their interests and how they influenced the collaboration; and 5) looking at technology as an active actor.

10.4 Recapitulation of Purpose and Findings

This dissertation starts by proposing a concept of team fluency for HIRC design tasks. Fluency is an essential construct for robots to be accepted as collaborators and team members in a human−robot team. It then introduces a novel digital-physical design workflow based on using digital simulations, a scanning device, feedback loops and a phase-changing material providing opportunities for HIRC during the form-finding design process. The dissertation designed and tested the generative design workflow through two case studies.

Finally, it introduces an evaluative framework and its metrics for the evaluation of key human elements affecting team fluency in human−robot design teams. Through the studies, it evaluated the proposed criteria for team fluency in a design task in which one human and one robot worked together by using distinct actions and informing each other to achieve a common goal. Team fluency was evaluated as a construct of its four main components: trust, collegiality, robustness, and improvement, each with its own set of downstream measures. The parameters were quantitatively and qualitatively evaluated before scoring their contribution to the perceived fluency. These metrics have to evolve and be refined and some need to be added or removed as the intellectual relationship between the designers and the robots evolves. The initial results of the design and evaluation framework, in the context of an intellectual evocative task, for untrained designers have been presented.

The results of the research presented can have significant practical implications. First, the proposed hierarchy of parameters and their distribution can provide a means for evaluating fluency between designers and industrial robots on the basis of empirical data. From a practical point of view, the presented set of measures would be a tool useful not only for quantifying and qualitatively understanding fluency in HIRC for designs tasks but also for assisting curriculum designers and education practitioners in understanding which system design characteristics can affect the designers' fluency in the human−robot task. For instance, the study identified three key design aspects fostering fluency and reliance in the human−robot team. Namely, translating design ideas into robotic actions, digital knowledge, and engagement, and a level of design maturity that allows systematisation. These three areas appear to be the major determinants of the fluency development. Furthermore, the laid-out parameters and their relationships can be used to identify the relationship of each individual designer and raise awareness regarding personal tendencies. For example, poor scores on attribution of credit, responsibility, and shared identity might identify those designers in need for an improved systematic thinking and conceptualisation of their design ideas. Characteristics that can be built up and reinforced through their education or professional development stages.

10.5 Contribution to Research

> *To have no technology is to be not-human; technology is a very large part of what makes us human. But our unconscious makes a distinction between technology as enslaving our nature versus technology as extending our nature. This is the correct distinction. We should not accept technology that deadens us… but that enhances us and affirms our humanness* (Arthur 2010).

The research presented in this dissertation aims to provide a unique perspective on the evaluation of the key human aspects of team fluency in a human−robot collaborative design task. It aims to help to understand and provide a perspective on why and when designers trust or do not trust robotic arms and which set of circumstances would enable them to hand-over the design agency to the robotic partner. Additionally, it aims to offer insights on how to build fluency in human−robot design teams.

HRC is a complex and fascinating area. It leads to questions of a philosophical and ethical nature. In the research presented here, humans were in control; they could decide whether the robot should proceed with the task and the ways in which it was going to do so. More sophisticated robots have now the ability to say ‘No’ to their human partner in high-risk situations where the safety of the robot is compromised. It can be argued that if the robot is appropriately configured for the task and well-understood by the user, its ability to refuse dangerous commands can be a useful asset. However, it can also be argued that humans should keep the last decision and robots should always remain subservient to the human. The new frontier of research in the field of robotics is offering machines that can work together with humans as peers. These new robots can take initiative and work in different ways to accomplish high-level goals with its human partner. However, even in these cases, the teaming between human and robot can be either synergistic or counterproductive, depending on the level of fluency in the system. Humans need to have a clear and accurate understanding of the robotic partner (Phillips et al. 2011).

Teams of human and robots designing together is a new territory. A new type of robot and design workflow where humans do not retain leadership through the entire process has to be designed. Relinquishing some of the control has to be accepted as part of a multi-agent design process. Humans might set the rules, but they should be prepared to accept a scenario where control and authority at certain points are given to the most appropriate team member, irrespective of whether it is a human or a machine. A futuristic robotic teammate will most likely fail, irrespective of its technological advancements, if the humans misunderstand what it is doing. Scoping how designers relate to robots and what characteristics would make for a successful human−robot relation becomes crucial for understanding and designing robots and workflows that designers will engage with in appropriate and successful ways.

Architectural research and practice are used to working with and adapting to machines and tools built for other industries. Examples of this range from software (e.g. architects adapting to animation software in their professional practice) to hardware, as demonstrated by the large number of industrial robot manipulators currently used in architecture design and research laboratories. However, the literature review suggested that the human error in human−robot collaborative systems is not only a function of the humans but also of how well the design of the system facilitates human understanding. The existing literature also suggests that human training does not always overcome the fluency and trust issues arising from poor system design. This dissertation provides cues on how the designer feels about human−robot interactions and what the designers' expectations are from a robotic partner. Designing an appropriate robot for designers and an interaction framework for such a system requires an understanding of the people that will use such a system, and of their world, the context of use, and what is meaningful to them (Kiesler and Hinds 2004). This can enable the design of a robotic system that can be successfully accepted and used by designers as a peer and as a partner, one in which the designer is comfortable delegating some design agency.

Roboticists have been researching and gaining practical experience in how to make robots that create comfortable experiences for people, track the user's positions, respond to spoken questions, avoid obstacles, react according to a changing environment, encourage cooperation, and promote a healthy rather than overly dependent relationship with humans. However, there is not much research on robots as intellectual human partners in the process of creation. This dissertation aimed to illustrate some of the principles and understanding needed to design robots and human−robot frameworks that can accomplish intellectually ambitious goals. It does not pretend to claim that these problems are new. Design explorations and research on human−robot interactions have existed in the field of robotics since at least the mid-1900s. However, the focus on robots as partners during an architectural design task and the delimitation of the parameters and the evaluation framework for the evaluation of design HIRC is something new.

Most of the research and published literature on architectural design related to robotics is concerned with the technical and material advances that have made robotics in architecture and digital fabrication possible. This problem is not unique to the architectural field, researchers in the fields of artificial intelligence (AI) and robotics acknowledge that 98% of the challenges in both the fields are of the social, ethical, legal, political, and ecological kind, and not 'technological' yet, only 2% of the time and resources dedicated to AI and robotics has been spent focusing on such issues (Pieters and Winiger 2016). The goal of this dissertation was to stretch the field of inquiry by focusing particularly on the behavioural and social aspects of the designer−robot collaboration, on what is important for designers in a robot partner, and on how robots can be improved to deal with the designers' needs. A key challenge in constructing robotic systems for architectural design is the identification of what the current needs of the domain are and what the future of the architectural design domain should be.

In conclusion, this work presents steps towards modelling design frameworks in the context of HRC during the design process, and of building robots for architectural designers understanding their world, perceptions, and needs. It approached these goals by proposing a novel design and evaluation framework that puts robots in the centre by including them as a creative partner in the early stages of design. The entire process was simulated, including the structure of the phase-changing materials, through a feedback loop with which the robot and the designer interacted and decided on the future steps throughout the phase-changing process of the material. It then proposed an evaluation framework of team fluency to evaluate the human–robot collaborative design activity. It used this design and evaluation framework in a joint design activity involving untrained human subjects to reveal insights into the human perceptions of robotic collaboration.

As far as the researcher knows, this is one of the first studies examining how designers respond to robots as collaborators during the design process. The research and the results presented in this dissertation can be seen as an early effort using theoretical and empirical foundations to inform the design of robots for architectural design tasks.

10.6 Autobiographical Reflection

Three main areas of research have advanced in the recent years, and thus, their integration is not only feasible but also necessary. These being robotics in architecture, physical sensors and machine learning (Appendix N). Interest in these three areas has led to the development of this dissertation. Combined, they enable robots to go beyond subservient model makers and become effective test beds for digital design ideas and novel materials. More importantly, they allow robots to become active partners that give feedback, suggestions, and have agency during the design process. This scenario allows architects to get involved with the material and design resources and understand their interactions from the early stages. Feedback will then come from precise experiments and physical mock ups in addition to that from digital simulations. Robotic and physical feedback is particularly useful when dealing with phase-changing, non-linear materials.

An important step towards their integration in the design process lies in understanding how humans feel and relate to the technology. One of the most immediate transformations when using robots is the need to make design procedures more explicit than in the past. An HIRC workflow needs to understand all the details and decision-making steps, even those which occur subconsciously or to *"deconstruct cognition"* (Rose 2017) to understand the human patterns of behaviour and action and identify the areas in which robots can collaborate. Current algorithmic and parametric techniques have started to make human decisions explicit, as design problems have to be explained to the computer, but adding a layer of physicality is a game changer, as randomness and unpredictability need to be accounted for. Additionally, craft and material processes, even for architects drawing construction details, are based on a large amount of tacit know-how (Picon 2004). Similar to Alexander's operating system for architecture (Steenson 2017), in RAD, materials and processes have to be developed to be understood by robots. Design and decision-making processes need to be externalised and made transparent to designers and robots as a means to enable collaboration.

Burnham (1970) observed that machines carry out brilliant dialogues with articulated people and very uninspired conversations, using the same software, with dull people. When the robot becomes an agent through the design process, how different and more interesting will designs be when created by accomplished designers? Who is to blame – the designer's skills or the machine – for bad design? Does the machine have any agency to change the results? Is this even possible? Any design resulting from the process is the result of the direct interaction between the human being and the 'program' irrespective of their idiosyncrasies.
Note that while computers can evaluate the final result on the basis of a series of established parameters, it is more difficult for them to evaluate a work in progress. This is because the

success criteria for both are very different: the evaluation of a design when the work is in progress is geared towards directing how to proceed. The design process tends to have a shifting target on the basis of the different goals that the designer might have and the process itself. In contrast, the evaluation of a finished product is concerned with whether it is good. Cohen; et al. (2012, p.102) described the inability of the machine to evaluate decisions during the design process as due to the fact that *"the machine knows that it has done a, b and c, but can't know that it has produced a novel and unanticipated relationship between a and c"*. RAD requires a holistic framework of different scientific and sociological fields to succeed in building a collaborative problem-solving robotic environment that augments the human designer.

10.7 Limitations

There are aspects of team fluency that were not addressed and should be considered for future work. These include: how to take into account the correct and incorrect actions of the robot and the human, how these measures can be applied when there is more than one human and one robot working together, and how larger human−robot mixed teams will perceive each other when there are more agents to blame or credit. The proposed evaluative framework also leaves room for extension in design exercises that include different materials, while still providing opportunities for human−robot collaborative design. These scenarios might need different objective metrics. Another aspect for further exploration is the division of tasks that was designed as part of the team structure. Removing sequential dependency and allowing for a flexible team structure in which the robot, informed by machine learning and other tools, can have intuition and take on other roles is crucial for more fluent HIRC.

Team fluency is currently a unidirectional construct in which the main concern is that of humans perceiving a fluent collaboration with the robot partner. However, as robots become more advanced, robots' understanding of human intent in cases when they have incomplete information becomes crucial for the collaboration. If robots are going to collaborate efficiently and partner with human designers, they would need to learn to adapt to the complexities of the design process, and like humans, part of the adaptation will come from the team fluency constructs. Variables indicating trustable, reliable, robust human partners and those who are not may need to be included. Ethical constructs such as robot self-preservation and the limits of its obedience to humans become relevant. As machine learning advances and robots become able to learn from their environment and the material they are manipulating and their humans in a connected world, they can also communicate this new knowledge between them. Team fluency then becomes a construct as enabled by humans as by robots.

10.8 Further Development of Design HIRC

As robots become smarter, their actions have an increasing effect compared to sensor-originating activities (Hoffman and Breazeal 2010). While this will enable a robot to be more independent, it may also interfere with the designer's motivation towards his or her preconceived design objective. In the current implementation, the agency was situational, and the participants could decide how much agency they would give to the robot after each iteration. Additionally, in the current model, the designer had to give some design agency to the robot because of its mechanical constraints, but he or she remained in control during the form-finding process. The agency exchange during the formation process, the team dynamics, and the intellectual mixture that it can cause, are fertile grounds for exploration.

Research addressing the role dynamics throughout a collaborative human−robot design session would be plausible by using machine learning to link material deformation to robot motion, allowing the measurement of how the roles of the robot and the designer change throughout the design process. An interesting question would be whether the trust in the robot design suggestions would alter the behaviour of the human partner, resulting in less engagement with the design task and less collaboration with the robot partner. Similar to human design teams, when roles are more dynamic, ownership over the design task changes, and for some teams, this has detrimental effects. Additionally, the bonding may be different with a smarter robot to which the designer can relinquish more control. A robot that has been trained and can learn about the material or the design task may have positive or negative effects on the bond between the human and the robot. Designers, in this task, felt comfortable with the robot because they saw it as non-intelligent. Future research should explore the following: How should the bonding effect that results from a smart robot offering suggestions to the designer be measured? When would designers relinquish more control? Would designers become more frustrated now that the robot can anticipate the results of their explorations? Is using machine learning to match the robot predictions to those of the human detrimental for the design activity? An intelligent or enhanced robot is currently out of the scope of this dissertation but will be an interesting topic to explore in future works.

A critical question going forward in this research, and with robots in architecture in general, is how to evaluate systems across varied levels of agency and automation. How can we predict the appropriate balance of agency versus automation given the nature of the design task? The research exercise showed that although designers were comfortable working with the robot, they had a clear preference to see themselves as the initiators, leads of critical actions, and leads of the design task. Interestingly, designers would not have the same problems accepting design suggestions from the digital design agents (software), as they had accepting design suggestions from the robot. The difference between shared digital and shared physical authorship with an intelligent machine requires further exploration. The focus should be on understanding where in the process would designers accept automation and what interactions with it would enable them to cede agency to the system and enjoy the collaboration. What would lead to the acceptance of algorithmic recommendations and shared physical authorship? What would lead to a shift in design thinking from design as an item to design as a flow where the trinity of human, material, and machine agencies is connected and continuously interacts along the process rather than being separate entities that stand in isolation imposing their desires over each other.

This dissertation evaluated the collaboration in two case studies consisting of three sessions each. It would be valuable to extend the application of the set principles over tasks with more sessions to understand how the human−robot relationship evolves as they become more comfortable with each other. Additionally, the framework was only tested with non-expert human designers. The effects of the proposed framework and metrics of team fluency on designers who are not necessarily robot experts but are relatively familiar with digital fabrication tools could be of interest on a side-by-side comparison controlled study of the collaborative design framework. The perceived fluency and trust in the robot partner might be significantly different and might need fine-tuning of the evaluation framework.

Substantial research is required to fully understand human−robot collaboration in design tasks. However, a validated set of metrics and the initial findings evaluating team fluency in a human−robot collaborative design scenario are a step forward towards robots being accepted as partners and collaborators during the design task. The research presented in this dissertation provides some insights that suggest how designers may respond to robotic manipulators with the shape of an industrial robot arm and which characteristics and attributes might be more desirable to improve the working relationship between both. The results also provide input regarding collaborative design workflows and the roles that robots might play inside them and throughout the design process. More broadly, this research represents an early effort to understand the characteristic and traits desired from a robot collaborator on a design task by using the theoretical and empirical foundations of social psychology and organisational behaviour. In contrast to other automated design processes where the roles of the human and the machine are defined *a priori*, the roles of different agents throughout the design process are not prescribed but are a continuous construct that emerges from each participant's decisions and interactions. Expanding this research would provide a holistic understanding of the human, machine and task factors for a successful implementation of HIRC in design tasks.

REFERENCES

A. Cosenzo, K. et al. 2006. Implementation of Automation for Control of Robotic Systems., p. 42.

Adler, P.A. and Adler, P. 1994. Observational techniques. In: *Handbook of qualitative research.* Thousand Oaks, CA, US: Sage Publications, Inc, pp. 377–392.

Ahlquist, S. and Menges, A. 2011. Behavior-based Computational Design Methodologies. In: *Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture*. Calgary, pp. 82–90.

Aimee, van W. 2013. A method for integrating ethics into the design of robots. *Industrial Robot: An International Journal* 40(5), pp. 433–440. Available at: https://doi.org/10.1108/IR-12-2012-451.

Alami, R. et al. 2006. Towards human-aware cognitive robots. *AAAI Workshop - Technical Report* WS-06-03, pp. 9–16.

Alberti, L.B. 1988. *On the Art of Building in Ten Books*. Rykwert, J. et al. eds. MIT Press.

Alexander, C. 2002. *The Nature of Order: An Essay on the Art of Building and the Nature of the Universe, Book 1 - The Phenomenon of Life*. 1st Editio. Center for Environmental Structure.

Alvesson, M. 2003. Beyond Neopositivists, Romantics, and Localists: A Reflexive Approach to Interviews in Organizational Research. *The Academy of Management Review* 28(1), pp. 13–33. Available at: http://www.jstor.org/stable/30040687.

Ammer, R. 2018. Make me think! the design of complexity. *Medium*

Arthur, W.B. 2010. *The Nature of Technology: What It Is and How It Evolves*. First Brit. Penguin.

Astley, W.G. and Zammuto, R.F. 1992. Organization science, managers, and language games. *Organization Science* 3(4), pp. 443–460. doi: 10.1287/orsc.3.4.443.

Ayres, P. 2006. Constructing the Specific. In: Oosterhuis, K. and Feireiss, L. eds. *Game Set and Match II*. Rotterdam: Episode Publishers, pp. 314–321.

Baldwin, D.A. and Baird, J.A. 2001. Discerning intentions in dynamic human action. *Trends in cognitive sciences* 5(4), pp. 171–178.

Barley, S.R. 1986. Technology as an Occasion for Structuring: Evidence from Observations of CT Scanners and the Social Order of Radiology Departments. *Administrative Science Quarterly* 31(1), pp. 78–108. Available at: http://www.jstor.org/stable/2392767.

Bartneck, C. et al. 2009a. Does the design of a robot influence its animacy and perceived intelligence? *International Journal of Social Robotics* 1(2), pp. 195–204. doi: 10.1007/s12369-009-0013-7.

Bartneck, C. et al. 2009b. Measuring Instruments for the Anthropomorhism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots. *International Journal of Social Robotics* 1(1), pp. 71–81. doi: https://doi.org/10.1007/s12369-008-0001-3.

Batliner, C. et al. 2016. User Interfaces for Live Robotic Control. In: Reinhardt, D. et al. eds. *Robotic fabrication in Architecture, Art and design*. Springer, pp. 377–387.

Baudrillard, J. 2005. *The System of Objects*. Verso Books.

Bazeley, P. 2013. *Qualitative Data Analysis*. 1st edition. London: SAGE Publications.

Bechthold, M. 2010. The Return of the Future: A Second Go at Robotic Construction. *Architectural Design* , pp. 116–121.

Belliger, A. and Krieger, D. 2016. *Organizing Networks - An Actor-Network Theory of Organizations*. transcript sociology.

Benfield, J.A. et al. 2007. Driver personality and anthropomorphic attributions of vehicle personality relate to reported aggressive driving tendencies. *Personality and Individual Differences* 42(2), pp. 247–258. Available at: http://www.sciencedirect.com/science/article/pii/S0191886906002789.

Benjamin, D. 2018. A lecture by David Benjamin. Available at: https://www.youtube.com/watch?v=DcCglwH_AcA.

Berscheid, E. and Peplau, A. 1983. The Emerging Science of Relationships. In: *Close Relationships*. New York: W.H. Freeman & Company, pp. 1–19.

Bhooshan, S. 2015. alice2017. Available at: https://github.com/shajayb/alice2017.

Bhooshan, S. and Sayed, M. El 2011. Use of Sub-division Surfaces in Architectural Form-Finding and Procedural Modelling. In: *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design*., pp. 60–67.

Billings, C.E. 1991. Human-centered aircraft automation: A concept and guidelines. *Nasa Technical Memorandum* (February). Available at: http://hdl.handle.net/2060/19910022821.

Billings, D.R. et al. 2012. Human-robot interaction: Developing trust in robots. *HRI'12 - Proceedings of the 7th Annual ACM/IEEE International Conference on Human-Robot Interaction* , pp. 109–110. doi: 10.1145/2157689.2157709.

Blair, S. 2015. IdeaHub, ABB launch new robotics accelerator programme.

Bock, T. and Langenberg, S. 2014. Changing building sites. *Architectural Design* 84(3), pp. 88–99.

Boltanski, L. and Chiapello, E. 2018. *The new spirit of Capitalism*. Verso Books.

Bonsignorio, F. 2015. The new AI and robotics: Lecture by Fabio Bonsignorio. Available at: http://robohub.org/the-new-ai-and-robotics-lecture-by-fabio-bonsignorio/ [Accessed: 12 March 2015].

Bonwetsch, T. et al. 2012. BrickDesign. In: *Robotic fabrication in Architecture, Art and design*. Wien: Springer, pp. 102–109.

Bonwetsch, T. 2012. Robotic Assembly Processes as a Driver in Architectural Design. *Nexus Network Journal* 14(3), pp. 483–494. doi: 10.1007/s00004-012-0119-3.

Borenstein, G. 2015. OpenCV for Processing. Available at: http://gregborenstein.com/.

Bortot, D. et al. 2013. Directly or on Detours? How Industrial Robots Approximate Humans. In: *8th ACM/IEEE Internation Conference on Human-Robot Interaction (HRI)*., pp. 89–90. doi: 10.1109/HRI.2013.6483515.

Bostrom, N. 2014. *Superintelligence: Paths, Dangers, Strategies*. OUP Oxford.

Bratman, M.E. 1992. Shared Cooperative Activity. *The Philosophical Review* 101(2), pp. 327–341.

Braumann, J. and Brell-Çokcan, S. 2012. Digital and Physical Computing for Industrial Robots in Architecture. *Beyond Codes and Pixels: Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA)* , pp. 317–326.

Braun, V. and Clarke, V. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3(2), pp. 77–101. Available at: http://dx.doi.org/10.1191/1478088706qp063oa.

Breazeal, C. and Scassellati, B. 2002. Robots that imitate humans. *Trends in cognitive sciences* 6, pp. 481–487. doi: 10.1016/S1364-6613(02)02016-8.

Britten, N. 1995. Qualitative Research: Qualitative interviews in medical research. *BMJ* 311(6999), pp. 251–253. Available at: https://www.bmj.com/content/311/6999/251.

Broadbent, E. et al. 2009. Acceptance of healthcare robots for the older population: Review and future directions. *International Journal of Social Robotics* 1(4), pp. 319–330. doi: 10.1007/s12369-009-0030-6.

Broadbent, E. et al. 2011. Mental schemas of robots as more human-like are associated with higher blood pressure and negative emotions in a human-robot Interaction. *International Journal of Social Robotics* 3(3), pp. 291–297. doi: 10.1007/s12369-011-0096-9.

Brooks, J. et al. 2015. The Utility of Template Analysis in Qualitative Psychology Research. *Qualitative research in psychology* 12(2), pp. 202–222. Available at: https://www.ncbi.nlm.nih.gov/pubmed/27499705.

Brown, S.D. and Capdevila, R. 1999. Perpetuum Mobile: Substance, Force and the Sociology of Translation. *The Sociological Review* 47(1_suppl), pp. 26–50. Available at: https://doi.org/10.1111/j.1467-954X.1999.tb03481.x.

Bruce, A. et al. 2002. The role of expressiveness and attention in human-robot interaction. *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292)* 4, pp. 38–42. doi: 10.1109/ROBOT.2002.1014396.

Bruemmer, D. et al. 2004. How to trust robots further than we can throw them., p. 1576. doi: 10.1145/985921.986152.

Brugnaro, G. 2017. Adaptive Robotic Training Methods for Subtractive Manufacturing. In: Nagakura, T. ed. *Acadia 2017 Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*., pp. 164–169.

Van den Brule, R. et al. 2014. Do Robot Performance and Behavioral Style affect Human Trust? *International Journal of Social Robotics* 6(4), pp. 519–531. Available at: http://link.springer.com/10.1007/s12369-014-0231-5.

Bryant, L.R. 2014. *Onto-Cartography*. Edinburgh University Press. Available at: https://books.google.co.uk/books?id=v-MkDQAAQBAJ.

Burghart, C.R. and Steinfeld, A. 2008. Proceedings of Metrics for Human-Robot Interaction, a Workshop at ACM/IEEE HRI 2008. *Computer* (March). Available at: http://www.hri-metrics.org/metrics08/index.html.

Burnham, J. 1970. Software - Information Technology: Its New Meaning for Art. In: Burnham, J. ed. *New York: Jewish Museum*. New York, p. 71.

Calitz, M.G. 2009. Chapter 5 Pilot Study., p. 33.

Callon, M. 1984. Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay. *The Sociological Review* 32(1_suppl), pp. 196–233. Available at: https://doi.org/10.1111/j.1467-954X.1984.tb00113.x.

Callon, M. 1990. Techno-economic Networks and Irreversibility. *The Sociological Review* 38(1_suppl), pp. 132–161. Available at: https://doi.org/10.1111/j.1467-954X.1990.tb03351.x.

Callon, M. and Latour, B. 1981. Unscrewing the Big Leviathan. In: Cicourel, A. V. and Knorr-Cetina, K. D. eds. *Advances in Social Theory and Methodology: Towards an Integration of Micro- and Macro-sociologies*. Routledge & Kegan Paul PLC, pp. 277–303.

Callon, M. and Latour, B. 1992. Do not Throw the Baby Out with the Bath School! A Reply to Collins and Yearley. In: Pickering, A. ed. Chicago: The University of Chicago Press, pp. 343–368.

Calo, R. et al. 2016. How should the law think about robots? *Robot Law* , pp. 3–22. doi: 10.4337/9781783476732.00007.

Cardoso, R. 2010. Craft versus design: moving beyond a tired dichotomy. In: *The Craft Reader*. New York: Berg, pp. 321–332.

Carpo, M. 2003. Drawing with numbers: Geometry and numeracy in early modern architectural design. *Journal of the Society of Architectural Historians* 62(4), pp. 448–469.

Carpo, M. 2004. Post-Hype Digital Architecture: From Irrational Exuberance to Irrational Despondency. *Grey Room* 14, pp. 102–115. Available at: http://www.jstor.org/stable/1262652.

Carpo, M. 2011. *The alphabet and the algorithm*. MIT Press.

Carpo, M. 2012. Digital Darwinism: Mass Collaboration, Form-Finding and the Dissolution of Authorship. *Log 26* 26(26), pp. 97–105.

Cecchi, N. 2015. Procedural Geometry: an interview with Aranda\Lasch. Available at: http://archinect.com/features/article/141844613/procedural-geometry-an-interview-with-aranda-lasch [Accessed: 6 January 2016].

Charalambous, G. 2014. *The development of a human factors tool for the successful implementation of industrial human-robot collaboration*. Cranfield University.

Charalambous, G. et al. 2016. The Development of a Scale to Evaluate Trust in Industrial Human-robot Collaboration. *International Journal of Social Robotics* 8(2), pp. 193–209. doi: 10.1007/s12369-015-0333-8.

Chen, J.Y.C. and Terrence, P.I. 2009. Effects of imperfect automation and individual differences on concurrent performance of military and robotics tasks in a simulated multitasking environment. *Ergonomics* 52(8), pp. 907–920. Available at: https://doi.org/10.1080/00140130802680773.

Chollet, F. 2018. If it's someone else's fault you don't really own it. Available at: https://twitter.com/fchollet/status/1062415651845754880.

Chua, C.K. et al. 2010. *Rapid Prototyping: Principles and Applications*. World Scientific.

CITA 2016. volvox. Available at: https://www.food4rhino.com/app/volvox.

Clark, A. 2003. *Natural-Born Cyborgs. Minds, Technologies, and the Future of Human Intelligence*. Oxford University Press.

Clarke, A. and Dawson, R. 1999. *Evaluation Research: An Introduction to Principles, Methods and Practice*. SAGE Publications. Available at: https://books.google.co.uk/books?id=4_FTxELbSbwC.

Coeckelbergh, M. 2011. Humans, animals, and robots: A phenomenological approach to human-robot relations. *International Journal of Social Robotics* 3(2), pp. 197–204. doi: 10.1007/s12369-010-0075-6.

Cohen;, H. et al. 2012. Evaluation of Creative Aesthetics. In: McCormack, J. and D'Inverno, M. eds. *Computers and Creativity*. Springer Berlin Heidelberg. doi: 10.1007/978-3-642-31727-9_4.

Cohen, P.R. and Levesque, H.J. 1991. Teamwork. *Noûs* 25(4), pp. 487–512. Available at: http://www.jstor.org/stable/2216075.

Cohen, S.G. and Bailey, D.E. 1997. What Makes Teams Work: Group Effectiveness Research from the Shop Floor to the Executive Suite. *Journal of Management* 23(3), pp. 239–290. Available at: https://doi.org/10.1177/014920639702300303.

Copi, I. et al. 2006. *Essential of Logic*. 2nd editio. Routledge.

Corke, P. 2015. Introduction to Robotics, robot futures.

Crabtree, B.F. and Miller, W.L. 1999. *Doing Qualitative Research*. SAGE Publications. Available at: https://books.google.co.uk/books?id=4ebxYPyY5noC.

Cressman, D. 2009. A brief overview of ANT - Punctualization, Heterogeneous Engineering and Translation. (1999), pp. 1–17.

Creswell, J.W. 1994. *Research design: qualitative & quantitative approaches*. Sage Publications. Available at: https://books.google.co.uk/books?id=B_d9AAAAIAAJ.

Creswell, J.W. 2007. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*. 3rd ed. Prentice Hall.

Creswell, J.W. 2014. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications. Available at: https://books.google.co.uk/books?id=PViMtOnJ1LcC.

Cuff, D. 1992. *Architecture: The Story of Practice*. MIT Press.

Daas, M. 2014. Toward a taxonomy of architectural robotics. *Sociedad Iberoamericana Grafica Digital (SIGRADI) 2014 Conference* 14, pp. 623–626.

Dawes, D.J. 2008. Do Data Characteristics Change According to the Number of Scale Points Used? An Experiment Using 5-Point, 7-Point and 10-Point Scales. *International Journal of Market Research* 50(1), pp. 61–104. Available at: https://doi.org/10.1177/147078530805000106.

Dawkins, R. 1976. *The Selfish Gene*. fourth edi. Oxford University Press.

DeLanda, M. 2004. Material Complexity. In: Leach, N. et al. eds. *Digital Tectonics*. Wiley Academy, pp. 14–21.

DeLanda, M. 2013. *Intensive Science and Virtual Philosophy*. revised. Bloomsbury Publishing. Available at: https://books.google.co.uk/books?id=tGYh0IGJ3wgC.

Dennett, D.C. 1987. *The intentional stance.* Cambridge, MA, US: The MIT Press.

Desai, M. et al. 2009. Creating trustworthy robots: Lessons and inspirations from automated systems. In:

Adaptive and Emergent Behaviour and Complex Systems - Proceedings of the 23rd Convention of the Society for the Study of Artificial Intelligence and Simulation of Behaviour, AISB 2009., pp. 49–56.

Dickinson, T.L. and McIntyre, R.M. 1997. A conceptual framework for teamwork measurement. In: *Team performance assessment and measurement: Theory, methods, and applications.* Series in applied psychology. Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers, pp. 19–43.

Dolwick, J.S. 2009. 'The Social' and Beyond: Introducing Actor-Network Theory. *Journal of Maritime Archaeology* 4(1), pp. 21–49. doi: 10.1007/s11457-009-9044-3.

Doolin, D.B. and Lowe, D.A. 2002. To Reveal is to Critique: Actor–Network Theory and Critical Information Systems Research. *Journal of Information Technology* 17(2), pp. 69–78. Available at: https://doi.org/10.1080/02683960210145986.

Dragan, A.D. et al. 2013. Legibility and predictability of robot motion. In: *2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*., pp. 301–308. doi: 10.1109/HRI.2013.6483603.

Drury, J.L. et al. 2003. Awareness in human-robot interactions. *IEEE Systems, Man and Cybernetics* 1(October), pp. 912–918. doi: 10.1109/ICSMC.2003.1243931.

Dubor, A. et al. 2016. Sensors and Workflow Evolutions: Developing a Framework for Instant Robotic Toolpath Revision. In: Reinhardt, D. et al. eds. *Robotic fabrication in Architecture, Art and design*. Springer, pp. 411–425.

Duffy, B.R. 2003. Anthropomorphism and the social robot. *Robotics and Autonomous Systems* 42(3–4), pp. 177–190. doi: 10.1016/S0921-8890(02)00374-3.

Dzindolet, M. et al. 2003. The role of trust in automation reliance. *International Journal of Human-Computer Studies* 58, pp. 697–718. doi: 10.1016/S1071-5819(03)00038-7.

Elashry, K. and Glynn, R. 2014. An approach to automated construction using adaptive programming. In: *Robotic fabrication in Architecture, Art and design*. Vienna: Springer, pp. 51–66.

Ellul, J. 1973. *The Technological Society*. Extensive. Random House.

ElMaraghy, H.A. 2005. Flexible and reconfigurable manufacturing systems paradigms. *International Journal of Flexible Manufacturing Systems* (4), pp. 261–276.

Endsley, M.R. 2006. Situation Awareness. In: Salvendy, G. ed. *Handbook of Human Factors and Ergonomics*. 3rd editio. New York: Wiley, pp. 528–542.

Energy, U.. D. of 2009. Doe Standard Human Performance Improvement Handbook Volume 1 : Concepts and Principles. 1(June)

Epps, G. 2014. Robofold and Robots.IO. *Architectural design: Made by robots* , pp. 68–69.

Ewalt, D.M. 2012. 30 great moments in the history of robots.

Faggella, D.G. 2013. *Explorations into the Philosophy of Transhumanism - A Lens to the Future Through the Thinkers of the Past*. Lighting Press.

Falcone, R. and Castelfranchi, C. 2000. Grounding autonomy adjustment on delegation and trust theory. *Journal of Experimental and Theoretical Artificial Intelligence* 12(2), pp. 149–151. doi: 10.1080/095281300409801.

Falcone, R. and Castelfranchi, C. 2001. The human in the loop of a delegated agent: The theory of adjustable social autonomy. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.* 31(5), pp. 406–418. doi: 10.1109/3468.952715.

Feringa, J. 2014. Entrepeneurship in architectural robotics: The simultaneity of craft, economics and design. *Architectural design: Made by robots* , p. 63.

Feringa, J. 2015. IaaC lecture series.

Fischer, G. 1995. Rethinking and reinventing artificial intelligence from the perspective of human-centered computational artifacts. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 991, pp. 1–11. doi: 10.1007/BFb0034793.

Fong, T. et al. 2001. Collaboration , Dialogue , and Human-Robot Interaction. In: *10th International Symposium of Robotics Research*. doi: : 10.1007/3-540-36460-9_17.

Fong, T. et al. 2006. The Human-Robot Interaction Operating System. 2006, pp. 41–48.

Fraser, K. et al. 2007. Team-based cellular manufacturing: A review and survey to identify important social factors. *Journal of Manufacturing Technology Management* 18(6), pp. 714–730. doi: 10.1108/17410380710763877.

Frels, R.K. and Onwuegbuzie, A.J. 2013. Administering quantitative instruments with qualitative interviews: A mixed research approach. *Journal of Counseling and Development* 91(2), pp. 184–194. doi: 10.1002/j.1556-6676.2013.00085.x.

Friedman, B. and Millett, L. 1995. 'It's the computer's fault' – Reasoning about computers as moral agents. In: *Proceedings of the CHI 1995, Conference on Human Factors on Computer Systems*. New York, pp. 226–227.

Friedman, Y. 1980. *Toward a Scientific Architecture*. MIT Press.

Friese, S. 2014. *Qualitative Data Analyisis with Atlas.ti*. 2nd Editio. London: SAGE Publications.

Galbraith, J.R. 1974. Organization Design: An Information Processing View. *Interfaces* 4(3), pp. 28–36. Available at: http://pubsonline.informs.org/doi/abs/10.1287/inte.4.3.28.

Gannon, M. 2018. *Human-Centered Interfaces for Autonomous Fabrication Machines*. Carnegie Mellon University.

Gao, F. et al. 2016. Designing for robust and effective teamwork in human-agent teams. *Robust Intelligence and Trust in Autonomous Systems* (919), pp. 167–190. doi: 10.1007/978-1-4899-7668-0_9.

GarcíadelCastilloyLópez, J.L. 2019. Machina . NET : A Library for Programming and Rear-Time Control.

Gerkey, B.P. and Matarić, M.J. 2004. A formal analysis and taxonomy of task allocation in multi-robot systems. *International Journal of Robotics Research* 23(9), pp. 939–954. doi: 10.1177/0278364904045564.

Gevarter, W.B. 1983. *An overview of artificial intelligence and robotics: volume 1--artificial intelligence, part A--the core ingredients*. NASA. Available at: https://books.google.co.uk/books?id=yODKxwEACAAJ.

Gevarter, W.B. 1985. *Intelligent Machines: an introductory perspective of artificial intelligence and robotics*. Prentice Hall.

Ghani, K.A. and Jayabalan, V. 2000. Advanced manufacturing technology and planned organizational change. *Journal of High Technology Management Research* 11(1), pp. 1–18. doi: 10.1016/S1047-8310(00)00018-3.

Gielniak, M.J. et al. 2013. Generating human-like motion for robots. *The International Journal of Robotics Research* 32(11), pp. 1275–1301. Available at: https://doi.org/10.1177/0278364913490533.

Gill, M.J. et al. 1998. On the genesis of confidence. *Journal of Personality and Social Psychology* 75(5), pp. 1101–1114. doi: 10.1017/S0022215100047289.

Glesne, C. 2005. *Becoming Qualitative Researchers: An Introduction*. 3rd ed. Allyn & Bacon.

Gliem, Joseph; Gliem, R.R. 2003. Calculating, Interpreting, And reporting Cronbach's Alpha Reliability Coefficient for Likert-Type Scales. In: *Midwest research to practice conference in adult, continuing, and community education*., pp. 82–88. Available at: https://scholarworks.iupui.edu/bitstream/handle/1805/344/Gliem & Gliem.pdf?s..

Goldberg, K. 2015. Let's Ditch the Singularity and Focus on Multiplicity. Available at: http://robohub.org/forget-singularity-lets-talk-multiplicity-ken-goldberg-on-ai-at-the-wef/ [Accessed: 2 February 2015].

Goodnow, J.J. 1996. Collaborative rules: how are people supposed to work with one another? In: Bates, P. P. and Staudinger, U. M. eds. *Interactive Minds: Life-Span Perspectives on the Social Foundation of Cognition*. Cambridge University Press, pp. 163–197.

Goodrich, M.A. and Schultz, A.C. 2007. Human – Robot Interaction : A Survey. *Foundations and Trends in Human–Computer Interaction* 1(3), pp. 203–275. doi: 10.1561/1100000005.

Gramazio, F. et al. 2014. *The robotic touch: How robots change architecture*. Park Books.

Gramazio, F. and Kohler, M. 2008. *Digital materiality in architecture*. Baden: Lars Müller Publishers.

Green, S.A. et al. 2008. Human robot collaboration: A Literature Review and Augmented Reality Approach in Design. *2007 Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007* 4(1), pp. 117–126. doi: 10.1115/DETC2007-34227.

Greyshed 2014. Workflows for Augmented Materiality. Available at: https://vimeo.com/116766943.

Groom, V. and Nass, C. 2007. Can robots be teammates? Benchmarks in human-robot teams. *Interaction Studies* 8(3), pp. 483–500. doi: 10.1075/gest.8.3.02str.

Groover, M.P. 2008. *Automation, Production Systems, and Computer-integrated Manufacturing*. Prentice Hall. Available at: https://books.google.co.uk/books?id=an-PTIoh_NoC.

Guba, E.G. and Lincoln, Y.S. 1994. Competing paradigms in qualitative research. In: *Handbook of qualitative research.* Thousand Oaks, CA, US: Sage Publications, Inc, pp. 105–117.

Hancock, P.A. et al. 1995. Influence of Task Demand Characteristics on Workload and Performance. *The International Journal of Aviation Psychology* 5(1), pp. 63–86. Available at: https://doi.org/10.1207/s15327108ijap0501_5.

Hancock, P.A. et al. 2011a. A meta-analysis of factors affecting trust in human-robot interaction. *Human Factors* 53(5), pp. 517–527. doi: 10.1177/0018720811417254.

Hancock, P.A. et al. 2011b. Can you trust your robot? *Ergonomics in Design: The quarterly of Human Factors Applications* 19(3), pp. 24–29. doi: 10.1177/1064804611415045.

Harman, G. 2009. *Prince of Networks: Bruno Latour and Metaphysics*. Melbourne: re.press.

Harriott, C.E. et al. 2015. Measuring Human Workload in a Collaborative Human-Robot Team. *Journal of Human-Robot Interaction* 4(2), p. 61. doi: 10.5898/jhri.4.2.harriott.

Hart, S.G. and Staveland, L.E. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In: Hancock, P. A. and Meshkati, N. eds. *Advances in Psychology, Volume 52*. North Holland, pp. 139–183. Available at: https://doi.org/10.1016/S0166-4115(08)62386-9.

Harvey, J.H. and Pauwels, B.G. 2009. Relationship Connection: A Redux on the Role of Minding and the Quality of Feeling Special in the Enhancement of Closeness. In: Lopez, S. J. and Snyder, C. R. eds. *The Oxford Handbook of Positive Psychology*. New York: Oxford University Press, pp. 385–392.

Hinds, P.J. et al. 2004. Whose Job Is It Anyway ? A Study of Human – Robot Interaction in a Collaborative Task. *Human-Computer Interaction* 19, pp. 151–181.

Hoffman, G. 2007. Ensemble: Fluency and Embodiment for Robots Acting with Humans. *Sciences-New York* (2000), p. 234.

Hoffman, G. 2013a. Evaluating Fluency in Human-Robot Collaboration. *HRI Workshop on Human Robot Collaboration, 2013.*

Hoffman, G. 2013b. Evaluating Fluency in Human-Robot Collaboration. *Robotics: Science and Systems, Workshop on Human Robot Collaboration* 381, pp. 1–8.

Hoffman, G. 2019. Evaluating Fluency in Human–Robot Collaboration. *IEEE Transactions on Human-Machine Systems* PP, pp. 1–10. Available at: https://ieeexplore.ieee.org/document/8678448/.

Hoffman, G. and Breazeal, C. 2007. Cost-based anticipatory action selection for human-robot fluency. *IEEE Transactions on Robotics* 23(5), pp. 952–961. doi: 10.1109/TRO.2007.907483.

Hoffman, G. and Breazeal, C. 2010. Effects of anticipatory perceptual simulation on practiced human-robot tasks. *Autonomous Robots* 28(4), pp. 403–423. doi: 10.1007/s10514-009-9166-3.

Hoffman, G. and Breazeal, C. 2012. Collaboration in Human-Robot Teams. *American Institute of Aeronautics and Astronautics* , pp. 1–18. doi: 10.2514/6.2004-6434.

Hoffman, G. and Weinberg, G. 2010. Synchronization in Human-Robot Musicianship., pp. 718–724.

Honey, M.A. 1987. The Interview as Text: Hermeneutics Considered as a Model for Analyzing the Clinically Informed Research Interview. *Human Development* 30(2), pp. 69–82. Available at: https://www.karger.com/DOI/10.1159/000273167.

Horvath, A.O. and Greenberg, L.S. 1989. Development and Validation of the Working Alliance Inventory. *Journal of Counseling Psychology* 36(2), pp. 223–233.

I/O, D. 2017. Mimic. Available at: .

Inoue, K. et al. 2005. Comparison of human psychology for real and virtual mobile manipulators. *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication* 2005(13), pp. 73–78. doi: 10.1109/ROMAN.2005.1513759.

Jabi, W. 2004. *A Framework For Computer-Supported Collaboration in Architectural Design*. University of Michigan.

Joe, J.C. et al. 2015. Function Allocation for Humans and Automation in the Context of Team Dynamics. *Procedia Manufacturing* 3(Ahfe), pp. 1225–1232. Available at: http://dx.doi.org/10.1016/j.promfg.2015.07.204.

Johannes Braumann 2017. *Visual Programming for Robots*. Available at: https://youtu.be/-Q77PHcyZ3E.

Johns, R.L. 2014. Augmented Materiality Modelling with Material Indeterminacy. In: *Fabricate: Making Digital Architecture*., pp. 216–223.

Johnson, P. and Duberley, J. 2000. Understanding Management Research. Available at: https://methods.sagepub.com/book/understanding-management-research.

Johnson, R.B. et al. 2007. Toward a Definition of Mixed Methods Research. *Journal of Mixed Methods Research* 1(2), pp. 112–133. Available at: https://doi.org/10.1177/1558689806298224.

Jones, E.E. and Nisbett, R.E. 1972. The Actor and the Observer: Divergent perceptions of the causes of behavior. In: *Attribution: Perceiving the Causes of Behavior*. Morristown, N.J.: General Learning Press, pp. 79–94.

Jones, H. and Rock, S. 2002. Dialogue-based human-robot interaction for space construction teams. *IEEE Aerospace Conference Proceedings* 7, pp. 3645–3653. doi: 10.1109/AERO.2002.1035340.

Ju, W. and Takayama, L. 2011. Should robots or people do these jobs? A survey of robotics experts and non-experts about which jobs robots should do. In: *IEEE International Conference on Intelligent Robots and Systems*. IEEE, pp. 2452–2459. doi: 10.1109/IROS.2011.6048367.

Kasparov, G. 2017. *Deep Thinking: Where Machine Intelligence Ends and Human Creativity Begins*. 1st editio. Public Affairs.

Keay, A. 2011. *A Robot , Slave or Companion Species? The naming practices and culture of robotics competitions*. University of Sydney.

Khatib, O. et al. 2004. Human-Centered Robotics and Interactive Haptic Simulation Oussama. *International Journal of Robotics Research* 23(2), pp. 167–178. doi: 10.1145/504729.504753.

Kidd, P.T. 1992. Design of human-centred robotic systems. In: Rahimi, M. and Karkowski, W. eds. *Human Robot Interaction*. London: Taylor and Francis, pp. 225–241.

Kiesler, S. and Goetz, J. 2003. Mental models of robotic assistants. *CHI 2002: Changing the world, changing ourselves* , p. 576. doi: 10.1145/506486.506491.

Kiesler, S. and Hinds, P. 2004. Introduction to This Special Issue on Human-Robot Interaction. *Human-Computer Interaction, Special Issue on Human-Robot Interaction* 19, pp. 1–8. doi: 10.1080/07370024.2004.9667337.

Kim, T. and Hinds, P. 2006. Who Should I Blame ? Effects of Autonomy and Transparency on Attributions in Human-Robot Interaction. In: *The 15th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN06)*. Hatfield, UK, pp. 80–85.

Kimura, H. et al. 1999. Task-model based human robot cooperation using vision. In: *Proceedings of the IEEE international conference on intelligent robots and systems*., pp. 701–706. doi:

10.1109/iros.1999.812762.

Kindberg, T. and Jones, T. 2007. “Merolyn the Phone”: A Study of Bluetooth Naming Practices. *UbiComp 2007: Ubiquitous Computing* (September), pp. 318–335. doi: 10.1007/978-3-540-74853-3_19.

King, N. 1998. Template Analysis. In: Symon, G. and Cassell, C. eds. *Qualitative Methods and Analysis in Organizational Research*. 1st Editio. Michigan: SAGE Publications, pp. 118–134.

King, N. and Horrocks, C. 2010. *Interviews in Qualitative Research*. SAGE Publications. Available at: https://books.google.co.uk/books?id=iOsnITKC48gC.

Kline, P. 2000. *The Handbook of Psychological Testing*. Routledge. Available at: https://books.google.co.uk/books?id=lm2RxaKaok8C.

Kline, T. 2005. Psychological Testing: A Practical Approach to Design and Evaluation. Available at: https://methods.sagepub.com/book/psychological-testing.

Kolarevic, B. and Klinger, K. 2008. *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. Routledge.

Kolata, G. 1998. scientific myths that are too good to die. *The New York Times* . Available at: http://www.nytimes.com/1998/12/06/weekinreview/scientific-myths-that-are-too-good-to-die.html?_r=0.

Koppula, H.S. and Saxena, A. 2016. Anticipating Human Activities Using Object Affordances for Reactive Robotic Response. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 38(1), pp. 14–29. doi: 10.1109/TPAMI.2015.2430335.

Kruijff, G.-J. and Janıcek, M. 2011. Using Doctrines for Human-Robot Collaboration to Guide Ethical Behavior. In: *AAAI fall symposium: robot-human teamwork in dynamic adverse environment.*, pp. 26–33. Available at: http://www.aaai.org/ocs/index.php/FSS/FSS11/paper/viewFile/4160/4477.

Kulic, D. and Croft, E. 2003. Estimating intent for human-robot interaction. *Advanced Robotics*

Kulić, D. and Croft, E. 2007. Physiological and subjective responses to articulated robot motion. *Robotica* 25(1), pp. 13–27. doi: 10.1017/S0263574706002955.

Kumar, R. 2014. *Research Methodology: A Step-by-Step Guide for Beginners*. SAGE Publications. Available at: https://books.google.co.uk/books?id=MKGVAgAAQBAJ.

Kvale, S. 2006. Dominance through interviews and dialogues. *Qualitative Inquiry* 12(3), pp. 480–500. doi: 10.1177/1077800406286235.

Landau, R. 1968. *New Directions in British Architecture*. Illustrate. Braziller, G. ed.

Lansdale, M.W. and Omerod, T.C. 1995. *Understanding interfaces: a handbook of human-computer dialogue*. Academic Press London.

Larsen, D. and Shore, J. 2018. The Agile Fluency Model.

Larson, C.E. and LaFasto, F.M.J. 1989. *Teamwork : what must go right, what can go wrong*. Sage Serie. Newbury Park, CA: Newbury Park, CA : Sage Publications.

Latour, B. 1987. *Science in Action: How to Follow Scientists and Engineers Through Society*. Harvard University Press. Available at: https://books.google.co.uk/books?id=sC4bk4DZXTQC.

Latour, B. 1993. *The Pasteurization of France*. Latour, B. Harvard University Press.

Latour, B. 1996. *Aramis, or the love of technology*. Harvard University Press.

Latour, B. 1999. *Pandora's Hope: Essays on the Reality of Science Studies*. Harvard University Press. Available at: https://books.google.co.uk/books?id=RMu6wbzVrVkC.

Latour, B. 2005. *Reassembling the Social: An introduction to Actor Network Theory*. Oxford University Press.

Law, J. 2007. Actor Network Therory and Material Semiotics. In: Turner, B. S. ed. *The new Blackwell companion to social theory*. Wiley - Blackwell, pp. 1–21.

Law, J. 2009. Actor network theory and material semiotics. *The New Blackwell Companion to Social Theory* (April), pp. 141–158. doi: 10.1002/9781444304992.ch7.

Law, J. and Hassard, J. 1999. *Actor Network Theory and After*. Wiley. Available at: https://books.google.co.uk/books?id=OsNv1Mq38-IC.

Lazar, J. et al. 2009. *Research Methods In Human-Computer Interaction*. 1st editio. John Wiley & Sons.

Lazar, J. et al. 2010. Research methods in human-computer interaction - Chapter 1. *Evaluation* , p. 426. Available at: http://books.google.com/books?hl=en&lr=&id=H_r6prUFpc4C&oi=fnd&pg=PT17&dq=RESEARCH+METHODS+IN+HUMAN-COMPUTER+INTERACTION&ots=xX61FobbFG&sig=coOHlvUNdv27XlQHjMB-eaidQBM.

Lee, J. and Moray, N. 1992. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics* 35(10), pp. 1243–1270. doi: 10.1080/00140139208967392.

Lee, J.D. et al. 2004. Trust in Automation: Designing for Appropriate Reliance. *Human Factors and Ergonomics Society* 46(1), pp. 50–80.

Lejeune, J.-F. and Bohl, C. 2009. *Sitte, Hegemann and the Metropolis: Modern Civic Art and International Exchanges*. 1st Editio. Routledge ed. Routledge.

Lem, S. 2014. *Summa Technologiae*. University of Minnesota Press.

Lenz, C. et al. 2008. Joint-action for humans and industrial robots for assembly tasks. *Proceedings of the 17th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN* , pp. 130–135. doi: 10.1109/ROMAN.2008.4600655.

Lewis, M.W. and Boyer, K.K. 2002. Factors impacting AMT implementation: An integrative and controlled study. *Journal of Engineering and Technology Management - JET-M* 19(2), pp. 111–130. doi: 10.1016/S0923-4748(02)00005-X.

Licklider J.C.R. 1960. Man-Computer Symbiosis. *IRE Transactions on Human Factors in Electronics* HFE-1, pp. 4–11.

Lim, J. 2014. Live robot programming. 3(2), pp. 165–175.

Lin, H. and Lin, Y. 2014. A Novel Teaching System for Industrial Robots. *Sensors* (ISSN 1424-8220), pp. 6012–6031. Available at: www.mdpi.com/journal/sensors.

Link, J. 2016. 5 ways architects are redefining craftsmanship for a postdigital age. *Archdaily* . Available at: https://www.archdaily.com/781960/5-ways-architects-are-redefining-craftsmanship-for-a-postdigital-age?ad_medium=gallery.

Lloret, E. et al. 2014. Complex concrete structures: Merging existing casting techniques with digital fabrication. *CAD Computer Aided Design* (Caadria), pp. 613–622. doi: 10.1016/j.cad.2014.02.011.

Lloyd Wright, F. 1901. The Art and Craft of the Machine. *Brush and Pencil* 8(2), pp. 77–81, 83-85,87-90. Available at: http://www.jstor.org/stable/25505640.

Loewenthal, K.M. 1996. *An introduction to psychological tests and scales.* London, England: UCL Press Limited.

Lomas, A. 2018. On Hybrid Creativity. *Arts* 7(3 The Machine as Artist (for the 21st Century)), p. 10. Available at: https://doi.org/10.3390/arts7030025.

Longhurst, R. 2003. Semi-structured Interviews and Focus Groups. In: Clifford, N. and Valentine, G. eds. *Key methods in geography*. London: SAGE, pp. 117–129.

Loukissas, Y.A. 2012. *Co-Designers: Cultures of Computer Simulation in Architecture*. New York: Routledge.

Lynn, G. 2008. *Form*. New York: Rizzoli International.

Lyotard, J.-F. 1984. *The Postmodern Condition: A Report on Knowledge*. Bennington, G. et al. eds. University of Minnesota Press.

Macefield, R. 2007. Usability Studies and the Hawthorne Effect. *Journal of Usability Studies* 2(3), pp. 145–154. Available at: http://www.usabilityprofessionals.org/upa_publications/jus/2007may/hawthorne-effect.pdf.

MacKenzie, I.S. 2013. Chapter 5 Designing HCI Experiments. In: *Human-Computer Interaction: An Empirical Research Perspective*. Morgan Kaufmann, p. 370.

Macmillan, J. et al. 2004. *Communication Overhead: The Hidden Cost of Team Cognition*. Washington, DC. doi: 10.1080/03637759309376288.

Madhavan, P. and Wiegmann, D.A. 2007. Similarities and differences between human–human and human–automation trust: An integrative review. *Theoretical Issues in Ergonomics Science* 8(4), pp. 277–301. doi: 10.1080/14639220500337708.

Mainprice, J. and Berenson, D. 2013. Human-robot collaborative manipulation planning using early prediction of human motion. *IEEE International Conference on Intelligent Robots and Systems* , pp. 299–306. doi: 10.1109/IROS.2013.6696368.

Malafouris, L. 2008. At the Potter ' s Wheel : An Argument for Material Agency. In: Knappett, C. and Malafouris, L. eds. *Material Agency: Towards a Non-Anthropocentric Approach*. Springer, pp. 19–37. doi: 10.1007/978-0-387-74711-8.

Marble, J.L. et al. 2004. Evaluation of Supervisory vs . Peer-Peer Interaction with Human-Robot Teams. In: *System sciences, 2004. proceedings of the 37th annual hawaii international conference*. IEEE, pp. 1–9.

Marquez, J.J. et al. 2017. *Human automation interaction*. Elsevier Ltd. Available at: https://doi.org/10.1016/B978-0-08-101869-9.00010-8.

Maxwell, S.E. and Delaney, H.D. 2004. *Designing Experiments and Analyzing Data: A Model Comparison Perspective*. 2nd editio. New York: NY: Psychology Press.

Mayer, M.P. et al. 2013. Using Anthropomorphism to Improve the Human-Machine Interaction in Industrial Environments (Part II). In: Duffy, V. G. ed. *Digital Human Modeling and Applications in Health, Safety, Ergonomics, and Risk Management. Human Body Modeling and Ergonomics*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 93–100.

Mayer, R.C. et al. 1995. An Integrative Model of Organizational Trust. *The Academy of Management Review* 20(3), pp. 709–734. Available at: https://www.jstor.org/stable/258792.

Mayo, E. 1933. *The human problems of an industrial civilization*. reprint ed. Routledge.

McCambridge, J. et al. 2014. Systematic review of the Hawthorne effect: New concepts are needed to study research participation effects. *Journal of Clinical Epidemiology* 67(3), pp. 267–277. Available at: http://dx.doi.org/10.1016/j.jclinepi.2013.08.015.

McCullough, M. 1997. *Abstracting Craft: The practiced digital hand*. Cambridge, Massachusets: MIT Press.

McDermott, C.M. and Stock, G.N. 1999. Organizational culture and advanced manufacturing technology implementation. *Journal of Operations Management* 17(5), pp. 521–533. Available at: http://www.sciencedirect.com/science/article/pii/S027269639900008X.

Mellis, D. et al. 2007. Arduino: An open electronic prototyping platform. *Proc. CHI* 2007, pp. 1–11.

Menges, A. 2016. Computational Material Culture. *Architectural Design* 86(2), pp. 76–83. Available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/ad.2027.

Menges, A. and Beesley, P. 2014. Achim Menges in conversation with Philip Beesley. In: Gramazio, F. et al. eds. *Fabricate: Negotiating Design and Making*. gta Verlag, pp. 156–165.

Merleau-Ponty, M. 2013. *Phenomenology of Perception*. Routledge.

Merriam-Webster 1828. Merriam - Webster dictionary. Available at: http://www.merriam-webster.com/dictionary/teamwork.

Mikolov, T. et al. 2013. Distributed Representations of Words and Phrases and their Compositionality. *Neural information processing systems* 1, pp. 1–9. Available at: https://arxiv.org/abs/1310.4546.

Miles, M.B. et al. 1994. *Qualitative Data Analysis: An Expanded Sourcebook*. SAGE Publications. Available at: https://books.google.co.uk/books?id=U4lU_-wJ5QEC.

Morel, P. 2014. Computation of revolution. *Made by Robots : challenging architecture at a larger scale* (229), pp. 76–87.

Morton, T. 2012. *The ecological thought*. Harvard University Press.

Mumford, L. 1963. *Technics and Civilization*. Harcourt, Brace & World. Available at: https://books.google.co.uk/books?id=KpktjwEACAAJ.

Mumford, L. 1967. *The Myth of the Machine: Technics and Human Development*. A Harvest / HBJ book.

Myers, N. 2008. Molecular embodiments and the body-work of modeling in protein crystallography. *Social studies of science* 38(2), pp. 163–199.

Nahmad Vazquez, A. et al. 2014. Design , Analysis and Fabrication of Expressive , Efficient Shell S tructures : A Prototype exploring synergy between architecture , engineering and manufacture. In:

PAULETTI, R. M. O. and M.L.R.F., R. eds. *International Association for Shell and Spatial Structures, IASS - SLTE*. Brasilia

Nahmad Vazquez, A. and Jabi, W. 2016. RAF | A framework for symbiotic agencies in robotic – aided fabrication. In: Weber, P. ed. *Proceedings of the International Peer-reviewed Conference on 'Research Based Education'*. The Bartlett School of Architecture, UCL, pp. 130–149.

Nass, C. et al. 1994. Computers are Social Actors. In: *Proceedings of the CHI'94 Conference on Human Factors in Computing Systems*. Boston, MA, pp. 72–78. doi: 10.1109/VSMM.2014.7136659.

Nass, C. and Moon, Y. 2000. Machines and Mindlessness: Social Responses to Computers. *Journal of Social Issues* 56(1), pp. 81–103.

Natsoulas, T. 1967. What are perceptual reports about? *Psychological Bulletin* 67(4), pp. 249–272. doi: 10.1037/h0024320.

Negroponte, N. 1969. Toward a Theory of Architecture Machines. *Journal of Architectural Education* 23(2), pp. 9–12.

Negroponte, N. 1973. *The Architecture Machine: Toward a More Human Environment*. MIT Press.

Nelson, T.H. 1970. The Crafting of Media. In: Burnham, J. ed. *SOFTWARE Information Technology: its new meaning for art*. New York, pp. 16–18.

Nick Cote 2017. *Intuitive Robotics*. Available at: https://youtu.be/qSQ-oqI741s.

Noble, D. 2011. *Forces of Production: A Social History of Industrial Automation*. 1st editio. Transaction Publishers.

Nomura, T. et al. 2006. Experimental investigation into influence of negative attitudes toward robots on human-robot interaction. *AI and Society* 20(2), pp. 138–150. doi: 10.1007/s00146-005-0012-7.

Norman, D.A. 1998. *The Invisible Computer*. Cambridge: MIT Press.

Norman, D.A. 2008. Simplicity is not the Answer. *ACM Interactions* 15(5)

Norman, D.A. 2010a. *Living with Complexity*. MIT Press.

Norman, G. 2010b. Likert scales, levels of measurement and the 'laws' of statistics. *Advances in Health Sciences Education* 15(5), pp. 625–632. doi: 10.1007/s10459-010-9222-y.

Nourbakhsh, I.R. 2013. *Robot Futures*. Cambridge, Massachusets: MIT Press.

OED Online 2017. Oxford English Dictionary Online. Available at: https://en.oxforddictionaries.com/definition/reliance.

Ogreten, S. et al. 2010. Recommended roles for uninhabited team members within mixed-initiative combat teams. In: *2010 International Symposium on Collaborative Technologies and Systems*., pp. 531–536. doi: 10.1109/CTS.2010.5478468.

Oliff, H. and Williams, M. 2018. Integrating Intelligence and Knowledge of Human Factors to Facilitate Collaboration in Manufacturing. In: *Proceedings of the ASME 2018 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2018*. Quebec, pp. 1–10.

Onwuegbuzie, A.J. et al. 2012. Qualitative analysis techniques for the review of the literature. *Qualitative Report* 17(28), pp. 1–28.

Onwuegbuzie, A.J. and Combs, J.P. 2011. Data Analysis in Mixed Research: A Primer. *International Journal of Education* 3(1), p. 13. doi: 10.5296/ije.v3i1.618.

Orlikowski, W.J. 2000. Using Technology and Constituting Structures: A Practice Lens for Studying Technology in Organizations. *Organization Science* 11(4), pp. 404–428. Available at: https://doi.org/10.1287/orsc.11.4.404.14600.

Ososky, S. et al. 2013. Building Appropriate Trust in Human-Robot Teams. In: *AAAI Spring Symposium: Trust and Autonomous Systems*., pp. 60–65. Available at: www.aaai.org.

Oxman, N. and Rosenberg, J.L. 2007. Material Performance Based Design Computation. In: *International conference on computer aided architectural design research*., pp. 5–11.

Oxman, N. and Rosenberg, J.L. 2009. Material-based Design Computation: An Inquiry into Digital Simulation of Physical Material Properties as Design Generators. *International Journal of Architectural Computing* 5(1), pp. 26–44. doi: 10.1260/147807707780912985.

Oxman, R. 2008. Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium. *Design Studies* 29, pp. 99–120. doi: 10.1016/j.destud.2007.12.003.

Özel, G. 2014. Case for an architectural singulariyt: Synchronization of robotically actuated motion, sense-based interaction and computational inference. In: Gerber, D. et al. eds. *Proceedings of the 34rd Annual Conference of the Association for Computer Aided Design in Architecture, ACADIA 2014*., pp. 399–408.

Parasuraman, R. et al. 1993. Performance Consequences of Automation Induced Complacency. *International Journal of Aviation Psychology* 3. doi: 10.1207/s15327108ijap0301_1.

Parasuraman, R. et al. 2000. A model for types and levels of human interaction with automation - Syst ems, Man and Cybernetics, Part A, IEEE Transactions on. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 30(3), pp. 286–297.

Parasuraman, R. et al. 2014. Human Trust in Other Humans, Automation, Robots, and Cognitive Agents: Neural Correlates and Design Implications. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 58(1), pp. 340–344. Available at: https://doi.org/10.1177/1541931214581070.

Parasuraman, R. and Riley, V. 1997. Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 39(2), pp. 230–253. Available at: http://journals.sagepub.com/doi/10.1518/001872097778543886.

Park, E. et al. 2008. Measuring Trust of Human Operators in New Generation Rescue Robots. *Proceedings of the JFPS International Symposium on Fluid Power* 2008(7–2), pp. 489–492. doi: 10.5739/isfp.2008.489.

Park, K.S. and Han, S.W. 2002. Performance obstacles in cellular manufacturing implementation-empirical investigation. *Human Factors and Ergonomics In Manufacturing* 12(1), pp. 17–29. doi: 10.1002/hfm.10000.

Parsons, H. 1974. What Happened at Hawthorne? *Science* 183(1972), pp. 922–932. doi: 10.1126/science.183.4128.922.

Patton, M.Q. 2001. *Qualitative Research & Evaluation Methods*. 3rd editio. Saint Paul, MN: SAGE Publications.

Pellegrinelli, S. et al. 2016a. Human-robot shared workspace collaboration via hindsight optimization. *IEEE International Conference on Intelligent Robots and Systems* 2016-Novem(ii), pp. 831–838. doi: 10.1109/IROS.2016.7759147.

Peng, H. et al. 2018. Roma: Interactive fabrication with augmented reality and a Robotic 3D printer. *Conference on Human Factors in Computing Systems - Proceedings* 2018-April. doi: 10.1145/3173574.3174153.

Pfeifer, R. and Bongard, J. 2006. *How the body shapes the way we think*. Cambridge: MIT Press, A Bradford book.

Phillips, E. et al. 2011. From tools to teammates: Toward the development of appropriate mental models for intelligent robots. In: *Proceedings of the Human Factors and Ergonomics Society*., pp. 1491–1495. doi: 10.1177/1071181311551310.

Pickering, A. 1995. *The Mangle of Practice: Time, Agency and Science*. The University of Chicago Press.

Pickering, A. 2011. *The Cybernetic Brain*. University of Chicago Press.

Picon, A. 2004. Architecture and the Virtual: Towards a New Materiality. *PRAXIS: Journal of Writing + Building* 6, pp. 114–121.

Picon, A. 2010. *Digital Culture in Architecture*. Basel: Birkhauser Architecture.

Picon, A. 2016. Symposium Advancements in Design Computation. Available at: https://www.youtube.com/watch?v=7H0lTzsBH68.

Pieters, R. and Winiger, S. 2016. Creative AI On the Democratisation and Escalation of Creativity. *Medium* , p. 15. Available at: https://medium.com/@creativeai/creativeai-9d4b2346faf3.

Pina, P. et al. 2008. Identifying Generalizable Metric Classes to Evaluate Human-Robot Teams. In: *Workshop on Metrics for Human-Robot-Interaction*. Amsterdam, p. 13.

Poljanšek, T. 2015. Choosing Appropriate Paradigmatic Examples for Understanding Collective Agency. In: Misselhorn, C. ed. *Collective Agency and Cooperation in Natural and Artificial Systems: Explanation, Implementation and Simulation*. Cham: Springer International Publishing, pp. 185–203. Available at: https://doi.org/10.1007/978-3-319-15515-9_10.

Protevi, J. 2005. *The Edinburgh Dictionary of Continental Philosophy*. Edinburgh university press.

Pye, D. 1968. *The nature and art of workmanship*. London: Cambridge University Press.

Rapley, T. 2012. The SAGE Handbook of Interview Research: The Complexity of the Craft. Available at: https://methods.sagepub.com/book/handbook-of-interview-research-2e.

Raspall, F. et al. 2014. Material Feedback in Robotic Production. In: McGee, W. and Leon, M. P. de eds. *Robotic fabrication in Architecture, Art and design*. Springer, pp. 333–345.

Rau, P.L.P. et al. 2010. A cross-cultural study: Effect of robot appearance and task. *International Journal of Social Robotics* 2(2), pp. 175–186. doi: 10.1007/s12369-010-0056-9.

Reeves, D. 2015. Spatial Slur. Available at: https://github.com/daveReeves/SpatialSlur.

Reiser, J. 2006. *Atlas of Novel Tectonics*. Princeton Architectural Press.

Rob|Arch 2019. map-of-creative-robots @ www.robotsinarchitecture.org. Available at: http://www.robotsinarchitecture.org/map-of-creative-robots [Accessed: 22 September 2019].

Rose, G. 2017. Canadian AI Company Uses Humans To Mentor Robots. *EIDEARD* . Available at: https://eideard.com/2017/03/02/canadian-ai-company-uses-humans-to-mentor-robots/.

Ross, L. 1977. The Intuitive Psychologist And His Shortcomings: Distortions in the Attribution Process. *Advances in Experimental Social Psychology* 10(C), pp. 173–220. doi: 10.1016/S0065-2601(08)60357-3.

Roudavski, S. 2011. Selective Jamming : Digital Architectural Design in Foundation Courses. *International Journal of Architectural Computing* 09(04), pp. 437–462. doi: 10.1260/1478-0771.9.4.437.

Rouse, W.B. et al. 1992. The role of mental models in team performance in Complex Systems. *IEEE transactions on systems, man and cybernetics* 22(6), pp. 1296–1308.

Saerbeck, M. and Bartneck, C. 2010. Perception of Affect Elicited by Robot Motion. *Proceeding of the 5th ACM/IEEE international conference on Human-robot interaction - HRI '10* , pp. 53–60. Available at: http://portal.acm.org/citation.cfm?doid=1734454.1734473.

Salas, E. et al. 2008. On Teams, Teamwork, and Team Performance: Discoveries and Developments. *Human Factors* 50(3), pp. 540–547. Available at: https://doi.org/10.1518/001872008X288457.

Sass, L. and Oxman, R. 2006. Materializing design: The implications of rapid prototyping in digital design. *Design Studies* 27(3), pp. 325–355. doi: 10.1016/j.destud.2005.11.009.

Scholtz, J. 2002b. Human Robot Interactions : Creating Synergistic Cyber Forces. In: *Multi-Robot Systems: From Swarms to Intelligent Automata*. Springer, Dordrecht, pp. 177–184.

Schon, D.A. 1984. *The Reflective Practitioner: How Professionals Think in Action*. Basic Books.

Schon, D.A. 1988. Designing: Rules, types and words. *Design studies* 9(3), pp. 181–190.

Schrempf, O.C. et al. 2005. A novel approach to proactive human-robot cooperation. *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication* 2005, pp. 555–560. doi: 10.1109/ROMAN.2005.1513838.

Schwartz, T. et al. 2014. All Bent Out..... In: McGee, W. and Leon, M. P. de eds. *Robotic fabrication in Architecture, Art and design*. Springer, pp. 305–317.

Seago, A. and Dunne, A. 1999. New methodologies in art and design research: the object as discourse. *Design Issues* 15(2), pp. 11–17. Available at: internal-pdf:/New Methodologies in Art and Design Research.pdf.

Sennet, R. 2009. *The Craftsman*. Penguin.

Shaw-garlock, G. 2010. Loving Machines : Theorizing Human and Sociable-Technology Interaction. In: *International Conference on Human-Robot Personal Relationship*. Springer Berlin Heidelberg, pp. 1–10.

Sheil, B. 2010. Protoarchitecture.

Sheil, B. 2012. Distinguishing Between the Drawn and the Made. *Architectural Design Special Issue: Material Computation: Higher Integration in Morphogenetic Design* 82(2), pp. 136–141. doi: 10.1002/ad.1390.

Sheridan, T.B. 1997. Eight ultimate challenges of human-robot communication. *Robot and Human Communication, 1997. RO-MAN '97. Proceedings., 6th IEEE International Workshop on* , pp. 9–14.

Shneiderman, B. 2008. Science 2.0. *Science* 319(March), pp. 1349–1351. Available at: 10.1126/science.1153539.

Siino, R. and Hinds, P. 2004. Making Sense Of New Technology As A Lead-In To Structuring: The Case Of An Autonomous Mobile Robot. *Academy of Management Proceedings* 2004, pp. E1–E6. doi: 10.5465/AMBPP.2004.13862508.

Singer, S. and Akin, D. 2012. A Survey of Quantitative Team Performance Metrics For Human-Robot Collaboration. (July), pp. 1–19. doi: 10.2514/6.2011-5248.

Snow, C.P. 2012. *The two cultures*. Reissue ed. Cambridge University Press.

Speaks, M. 2011. Lecture at University of Michigan, Taubman college. Available at: https://www.youtube.com/watch?v=2ISnW0cuV5Y.

Steenson, M.W. 2014. *Architectures of Information: Christopher Alexander, Cedric Price, and Nicholas Negroponte & MIT'S Architecture Machine Group*. Princeton University.

Steenson, M.W. 2017. *Architectural Intelligence: How Designers and Architects Created the Digital Landscape*. MIT Press.

Steinfeld, A. et al. 2006. Common Metrics for Human-Robot Interaction. In: *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*. ACM, pp. 33–40. doi: 10.1136/gut.42.3.410.

Steinhagen, G. et al. 2016. Path Planning for Robotic Artistic Stone Surface Production. In: Reinhardt, D. et al. eds. *Robotic Fabrication in Architecture, Art and Design 2016*. Springer, Cham, pp. 122–135. doi: https://doi.org/10.1007/978-3-319-26378-6_9.

Strodtbeck, F.L.. et al. 1957. Social Status in Jury Deliberations. *American Sociological Review* 22(6), pp. 713–719.

Suchman, L.A. 1987. *Plans and Situated Actions: The Problem of Human-machine Communication*. New York, NY, USA: Cambridge University Press.

Tatnall, A. and Gilding, A. 1999. Actor-Network Theory and Information Systems Research.

Van Teijlingen, E. and Hundley, V. 2002. The Importance of Pilot Studies. *Nursing standard (Royal College of Nursing (Great Britain) : 1987)* 16, pp. 33–36. doi: 10.7748/ns2002.06.16.40.33.c3214.

Terveen, L.G. 1995. Overview of human-computer collaboration. *Knowledge-Based Systems* 8(2–3), pp. 67–81. doi: 10.1016/0950-7051(95)98369-H.

Thabane, L. et al. 2010. A tutorial on pilot studies: the what, why and how. *BMC Medical Research Methodology* 10(1), p. 1. Available at: https://doi.org/10.1186/1471-2288-10-1.

Thompson, R. 2007. *Manufacturing processes for design professionals*. New York: Thames & Hudson.

Tripp, D. 2005. Action research : a methodological introduction. *pr* . Available at: www.scielo.br/pdf/ep/v31n3/en_a09v31n3.pdf.

Trist, E.L. and Bamforth, K.W. 1951. Some Social and Psychological Consequences of the Longwall Method of Coal-Getting: An Examination of the Psychological Situation and Defences of a Work Group in

Relation to the Social Structure and Technological Content of the Work System. *Human Relations* 4(1), pp. 3–38. Available at: https://doi.org/10.1177/001872675100400101.

Tsigkari, M. et al. 2013. Integrated Design in the Simulation Process. In: *Proceedings of the Symposium on Simulation for Architecture & Urban Design*. SimAUD '13. San Diego, CA, USA: Society for Computer Simulation International, pp. 28:1--28:8. Available at: http://dl.acm.org/citation.cfm?id=2500004.2500032.

Tsui, K. et al. 2010. Considering the bystander's perspective for indirect human-robot interaction. In: *Proceedings of the 5th ACM/IEEE International Conference on Human Robot Interaction.*, pp. 129–130. doi: 10.1109/HRI.2010.5453230.

Unhelkar, V. V. et al. 2014. Comparative performance of human and mobile robotic assistants in collaborative fetch-and-deliver tasks. *ACM/IEEE International Conference on Human-Robot Interaction* , pp. 82–89. doi: 10.1145/2559636.2559655.

Vertesi, J. 2012. Seeing like a Rover : Visualization , embodiment , and interaction on the Mars Exploration Rover Mission. *Social Studies of Science* 42(3), pp. 393–414. doi: 10.1177/0306312712444645.

Waldeck, N.E. 2000. *Advanced Manufacturing Technologies and Workforce Development*. Garland Pub. Available at: https://books.google.co.uk/books?id=eVgH751Vv1UC.

Walsham, G. 1997. Actor-Network Theory and IS Research : Current Status and Future Prospects. In: *Information Systems and Qualitative Research*. Springer US, pp. 466–480.

Watkins, D. and Gioia, D. 2015. *Mixed Methods Research*. Oxford University Press. Available at: https://books.google.co.uk/books?id=U4a-CQAAQBAJ.

Weiser, M. 1991. The Computer for the 21st Century. *Scientific American* 265(3), pp. 94–104.

Wickens, C.D. and Hollands, J.G. 2000. *Engineering psychology and human performance*. 3rd editio. Prentice Hall.

Wiener, N. 1950. *The Human Use Of Human Beings: Cybernetics And Society*. New Editio. Da Capo Press.

Williams, N. et al. 2011. A Case Study of a Collaborative Digital Workflow in the Design and Production of Formwork for 'Non-Standard' Concrete Structures. *International Journal of Architectural Computing* 9(3), pp. 223–240. doi: 10.1260/1478-0771.9.3.223.

Willmann, J. 2015. The otherness of the machine. *Cube Magazine, Uncanny Valley* , pp. 38–44.

Wilson, E.O. 2000. *Sociobiology: The New Synthesis*. 2nd New Ed. Harvard University Press.

Windisch, K.G. 2010. *Inanimate reason; or a circumstantial account of that astonishing piece of mechanism, M. de Kempelen's chess-player; now exhibiting at No. 8, Savile-Row, Burlington-Gardens*. Gale ECCO, Print editions.

Witt, A.J. 2010. A Machine Epistemology in Architecture. Encapsulated Knowledge and the Instrumentation of Design. *Candide. Journal for architectural knowledge* 03(03), pp. 37–88.

Wittink, D.R. and Bayer, L.R. 2003. The measurement imperative. *Marketing Research* 15(3), pp. 19–23.

Wolf, C.G. et al. 1989. The role of laboratory experiments in HCI: help, hindrance, or ho-hum? *ACM SIGCHI Bulletin* 20(SI), pp. 265–268. Available at: http://portal.acm.org/citation.cfm?doid=67450.67500.

Wörn, H. and Längle, T. 2000. Cooperation Between Human Beings And Robot Systems In An Industrial Environment. *Microelectronics Reliability*

Wright, P. and McCarthy, J. 2015. The Politics and Aesthetics of Participatory HCI. *Interactions* 22(6), pp. 26–31. doi: 10.1145/2828428.

Wright, S. 2015. Exploring Actor-Network Theory And CAQDAS Provisional Principles And Practices For Coding , Connecting And Describing Data Using ATLAS . ti. In: *Qualitative Data Analysis and beyond - proceedings of the ATLAS.ti User Conference 2015*. Berlin: Technische Universitat Berlin

Xu, S. et al. 2015. Assembly of micro/nanomaterials into complex, three-dimensional architectures by compressive buckling. *Science* 347(6218), pp. 154–159.

Yagoda, R.E. and Gillan, D.J. 2012. You Want Me to Trust a ROBOT? The Development of a Human-Robot Interaction Trust Scale. *International Journal of Social Robotics* 4(3), pp. 235–248. doi: 10.1007/s12369-012-0144-0.

Yanco, H.A. and Drury, J.L. 2002. A Taxonomy for Human-Robot Interaction. *Proceedings of the AAAI Fall Symposium on Human-Robot Interaction* , pp. 111–119. doi: 10.1109/ICSMC.2004.1400783.

Ye, B.C. and Tsukruk, V. V 2015. Designing two-dimensional materials that spring rapidly into three-dimensional shapes. *Science* 347, pp. 130–131.

APPENDICES

APPENDIX A THE QUANTITATIVE QUESTIONNAIRE

Participant number: __________

COLLABORATION WITH AN INDUSTRIAL ROBOT

01. The way the robot moved made me feel

Highly Uncomfortable	Uncomfortable	Neutral	Comfortable	Highly Comfortable

02. I felt the robot was going to do what it was supposed to do

Very Unreliably	Unreliably	Neutral	Reliably	Very Reliably

03. The speed at which the robot performed it tasks made me feel

Highly Uncomfortable	Uncomfortable	Neutral	Comfortable	Highly Comfortable

04. I felt while interacting with the robot:

Very Unsafe	Unsafe	Neutral	Safe	Very Safe

05. The robot moving in the expected way was

Strongly Concerning	Concerning	Neutral	Non-concerning	Strongly Non-concerning

06. I knew the scanning information from the robot would be

Highly Inaccurate	Inaccurate	Neutral	Accurate	Highly Accurate

07. The information from the scanning was useful for my downstream design decisions

Very Unhelpful	Unhelpful	Neutral	Helpful	Very Helpful

08. By looking at the deformation of the material I could decide my next move

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

09. I felt the information given by the robot was

Very Useless	Useless	Neutral	Useful	Very Useful

10. The size of the robot was

Highly Intimidating	Intimidating	Neutral	Encouraging	Highly Encouraging

11. The robot cutting and pushing tools seemed

Highly Unreliable	Unreliable	Neutral	Reliable	Highly Reliable

12. I was comfortable the robot would not hurt me

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

13. I trusted that to cooperate with the robot was

Very Unsafe	Unsafe	Neutral	Safe	Very Safe

14. The scanning, cutting and pushing (robot actions) seemed like they could be

Highly Unreliable	Unreliable	Neutral	Reliable	Highly Reliable

15. If I had more experiences with other robots, I would feel about this task

Highly Concerned	Concerned	Neutral	Unconcerned	Highly Unconcerned

16. The complexity level of the task made working with the robot

Very Uncomfortable	Uncomfortable	Neutral	Comfortable	Very Comfortable

17. If the task was more complicated and I had to work with the robot I might have felt

Highly Concerned	Concerned	Neutral	Unconcerned	Highly Unconcerned

18. I might not have been able to work with the robot had the task been more complex

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

19. The task made interaction with the robot

Very Easy	Easy	Neutral	Complex	Very Complex

20. I believe the robot likes me

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

RELIANCE ON THE ROBOT

Please grade the following statements regarding the robot and your work with it from 1 'not at all' to 7 'fully'.

21. To what extent does the robot have characteristics that you would expect from a human partner doing the same tasks

(not at all)	1	2	3	4	5	6	7	(fully)

22. To what extent did you feel it was only your job to perform well on the task

(not at all)	1	2	3	4	5	6	7	(fully)

23. To what extent did you feel ownership of the task

(not at all)	1	2	3	4	5	6	7	(fully)

24. To what extent did you feel that your performance on this task was out of your hands

(not at all) 1 2 3 4 5 6 7 (fully)

25. The success of the task was largely due to the things I did

(not at all) 1 2 3 4 5 6 7 (fully)

26. I am responsible for most things that we did well on the task

(not at all) 1 2 3 4 5 6 7 (fully)

27. Our success was largely due to the things the robot did

(not at all) 1 2 3 4 5 6 7 (fully)

28. The robot should get credit for most of what is accomplished on this task

(not at all) 1 2 3 4 5 6 7 (fully)

29. I hold the robot responsible for any errors that were made on this task

(not at all) 1 2 3 4 5 6 7 (fully)

30. The robot is to blame for most of the problems that we encountered in accomplishing this task

(not at all) 1 2 3 4 5 6 7 (fully)

31. The robot and I improved our performance on this task over time

(not at all) 1 2 3 4 5 6 7 (fully)

32. The performance of the robot in this task improved over time

(not at all) 1 2 3 4 5 6 7 (fully)

33. My performance in this task improved over time

(not at all) 1 2 3 4 5 6 7 (fully)

34. The robot was a partner for me in this task

(not at all) 1 2 3 4 5 6 7 (fully)

35. The robot help me perform better this task

(not at all) 1 2 3 4 5 6 7 (fully)

36. How will you call the robot? (suggest a name)

APPENDIX B INTERVIEW SCHEDULE

Themes

The robotic arm and the design process

- What are the strengths and weaknesses of a tool like the robot arm?
- Which of these weaknesses are the most challenging to overcome and which are the least?
- What did you learn in the process that might have changed your initial approach?
- What would you do exactly the same way?

Using the robotic arm to develop the design.

- In what way did it aid your creative process?
- In what ways did it hinder your process?
- How did it shape you overall vision for the project?
- Were there things about this tool that seemed more challenging, confusing or limiting than was necessary?
- Were there things that you were hoping to achieve that you couldn't because of the limits in the tool?
- What would have been required to get around these limits?

The connection between design and material

- What are the strengths and weaknesses of doing physical models through your design process?
- Do you think is better to make them at the end, once the design is in a good state?
- Did the information that the robot gave you about the material helped in your design?
- Was the robot accurate in forming the material?
- Did you changed your design after seeing some of the initial results?

- Thinking on the task you just finished, what would you design differently?
- Why?

Trust

- Can you talk about your first thoughts regarding the interaction with this robot?
- Why did you feel this way?
- Did you feel you could rely on the robot to perform his tasks- cutting, pushing and scanning- safely?
- Can you talk about the robot's ability to push, scan and provide you with enough information to continue your design process?
- How did the appearance of the robot influence your trust? Why?
- Did you have any concerns when you interacted with the robot? Why?
- Considering the task, you just completed, what has encouraged you to trust the robot?
- Is there anything else about the robot that encouraged you to trust this robot?

APPENDIX C ETHICS APPROVAL

EC1609.294

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STAFF AND PHD/MPHIL PROJECTS

wsa

Tick one box:	☐ STAFF ☑ PHD/MPHIL
Title of project:	"A Framework for Robotic Assisted Design: Explorations of Industrial Robotics In Architectural Design"
Name of researcher(s):	Alicia Nahmad Vazquez
Name of principal investigator	
Contact e-mail address:	nahmadvazqueza@cardiff.ac.uk
Date:	27.September.2016

Participants		YES	NO	N/A
Does the research involve participants from any of the following groups?	• Children (under 16 years of age)		/	
	• People with learning difficulties		/	
	• Patients (NHS approval is required)		/	
	• People in custody		/	
	• People engaged in illegal activities		/	
	• Vulnerable elderly people		/	
	• Any other vulnerable group not listed here		/	
• When working with children: I have read the Interim Guidance for Researchers Working with Children and Young People (http://www.cardiff.ac.uk/archi/ethics_committee.php)				/

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	/		
• Will you tell participants that their participation is voluntary?	/		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	/		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	/		
• Will you give participants the option of omitting questions they do not want to answer?	/		
• If the research is observational, will you ask participants for their consent to being observed?	/		
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?	/		

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		/	
• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		/	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?			/	
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants	/		
	• allow the participants the option of anonymity for all or part of the information they provide	/		

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (http://www.cf.ac.uk/osheu/index.html)	/

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		/	
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		/	

[1] If any non-anonymous and/or personalised data be generated or stored, *written consent* is required.

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information. The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A **The Project** (provide all the information listed below in a separate attachment)

1. Title of Project
2. Purpose of the project and its academic rationale
3. Brief description of methods and measurements
4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria
5. Consent and participation information arrangements - please attached consent forms if they are to be used
6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them
7. Estimated start date and duration of project

All information must be submitted along with this form to the School Research Ethics Committee for consideration

Researcher's declaration (tick as appropriate)	
• I consider this project to have **negligible ethical implications** (*can only be used if none of the grey areas of the checklist have been ticked*).	/
• I consider this project research to have **some ethical implications**.	
• I consider this project to have **significant ethical implications**	

Signature [signature] **Name** ALICIA NAHMAD VAZQUEZ **Date** 27.09.16
Researcher or MPhil/PhD student

Signature [signature] **Name** WASSIM JABI **Date** 27/09/16
Lead investigator or supervisor

Advice from the School Research Ethics Committee

STATEMENT OF ETHICAL APPROVAL

This project had been considered using agreed Departmental procedures and is now approved

Signature [signature] **Name** PERCEET DAVIS **Date** 20.10.16
Chair, School Research Ethics Committee

APPENDIX D RISK ASSESSMENT

Risk Assessment WSA

1. General Information

Department	ARCHI	Building	Bute	Room number	2.30(a)
Assessor	Alicia Nahmad	**Date of Assessment**	16.10.2017	**Assessment number**	

2. Brief Description of procedure/activity including location and duration

Activity 1: Research participants will be introduced in groups of 3 – 4 people to the robot moves and operation. They will jog the robot in T1 and create a program using the teach pendant in order to understand its different constraints. They will be guided and supervised at all times by the researcher (KUKA certified operator) Activity 2: Participants will develop a design task individually with the robot. The task consists on: the robot cutting concrete canvas using a circular blade end effector, the robot pushing the concrete canvas using a wooden sphere and the robot scanning the result using a Kinect attached to the arm. The participant will then send new instructions to the robot based on this result. Participants will be outside the cage when the robot is moving and will be manipulating the concrete canvas material (attaching it to wooden frame, hydrating it) when the robot is not moving.

3. Assessment

What are the hazards	Who might be harmed	Existing controls	Likelihood of risk	Current risk level	What further action is necessary? Inc. by whom and when	Future risk level
Add further boxes as required.			Low Medium high	Low Medium High		
Medical emergency						
Travel						
Fieldwork						
Fire						
Manual handling	Participants due to cement powder when manipulating the concrete canvas material, specially before the hydrating stage.	Masks will be provided to all participants taking part on the experiment to cover their nose and mouth.	Low	Low		
Machinery/equipment	Participants due to collisions or contact with moving parts	Robotics Lab Risk Assessment	Low	Low		
Stress						
Slips/trips/falls	Participants tripping due to Kinect connection from P.C (outside cage) to robot arm (inside cage)	The cable will be on the back side of the robot, participants will be mainly working maninly on the front (where the table is) Duct tape will be used to cover the cable and a sign placed to indicate a cable there.	Low	Low	Alicia will cover the cable and put the sign. Also will arrange with IT the best way to connect the Kinect from the end of the robot arm to the computer processing the information.	
Electrical						
Working at height						

APPENDIX E PARTICIPANT INFORMATION SHEET

1. Research Project Title:
"A Framework for Robotic Assisted Design: Explorations of Industrial Robotics in Architectural Design"

2. Invitation paragraph
You are being invited to participate in this research project. Before you take a decision to participate or not, it is important for you to understand the purposes and implications of this research. Please take your time to read the following information carefully and do not hesitate to ask the researcher if something is not clear or if you would like to obtain more information. Thank you for reading this.

3. What is the project's purpose?
The aim of this research is to investigate the role of the industrial robot as a collaborator that augments the designer and is an active agent through the design process. I am attempting to understand what benefits do robots bring to the design activity and their role in shaping the architectural design process based on what kind of interactions form between the designer, the material and these artefacts.

4. Why have I been chosen?
You have been chosen to participate as you signed up for a research study which involves using industrial arms during the design process and your design, digital and robotic skills qualify you to take part on it.

5. Do I have to take part?
Your participation in the project is completely optional. If you decide to participate, you will be asked to read and sign a consent form, and you are free to withdraw at any time. If you choose not to participate in this research project, there will be no effect in any form that may affect your activities in the university.

6. What will happen to me if I take part?
If you decide to participate an initial introduction to the robotic arm will take place where you will be able to jog it around and record online programs with it. You will also have an introduction to digital design form-finding methods place and tools. Additionally, you will learn how to generate GCode and get feedback from the robot through a Kinect. During the whole process, you will be observed and technically assisted by me. I will take notes and record videos throughout the process. You can also expect me to ask you questions about your work with the robotic arm. A final questionnaire will be given to you to answer regarding your participation and experience. The purpose of the questionnaire is to understand what shapes your relationship with the industrial robotic manipulator and its influence on your design process.

7. What do I have to do?
You will be asked to do a design exercise using digital generative or form-finding tools and to fabricate it using the robot arm. The process will be iterative as you will be able to get information from the robot as feedback to add into your formation process. You will also be asked to provide comments about the questions asked and share your experiences during the process. Also, your behaviour during the design, fabrication and feedback process will be studied to see how you interact and relate to the robotic manipulator and its influence on your design process.
It is estimated that this project will take around 10 hours of your time distributed during the term as follow:

3 x 2hr sessions of introduction to the digital tools and digital workflow
1 x 3hr session of design task execution with the robot.

8. What are the possible disadvantages and risks of taking part?
No foreseeable disadvantages or risks exist if you take part in this project. All your comments will be made anonymous to protect your identity, and the confidential documents will be locked in a secured file cabinet.

9. What are the possible benefits of taking part?
There will be no material or monetary benefit for your participation. One of the benefits of your participation would be that your opinions and experiences may help to have a better understanding of how a robotic-assisted design framework can be implemented as part of the design process from very early stages. Based on your experiences some suggestions can be made to improve how designers are introduced to digital fabrication machines, specifically robotics.

10. What if something goes wrong?
If you have any problem or would like to make a complain regarding your treatment by the researcher, please feel free to contact my supervisor:

Supervisor:	Wassim Jabi
E-mail:	jabiW@cardiff.ac.uk
Address:	Room 2.65, Welsh School of Architecture Bute Building, King Edward VII Avenue Cardiff, CF10 3NB Wales, United Kingdom

11. Will my taking part in this project be kept confidential?
All information you may provide will be kept in strict confidentiality and anonymous. My supervisor and I are the only ones who will have access to the information you provided, and no attempt will be made to reveal your identity in the final report of the analysed data.

12. What type of information will be sought from me and why is the collection of this information relevant to achieving the research project's objectives?
I am attempting to collect information to unpack the relationship between designers and this specific digital fabrication tool. Industrial robotic arms have been around for over 40 years in the manufacturing industry, but their adoption by architectural research groups is fairly new. From these observations and interviews, I want to know what factors affect your participation in a design environment enabled by a robotic manipulator. Collecting this information would allow me to have a better understanding on how different designers participate in a robotic design environment and see how they create relationships with this new tool and which factors affect their participation within a holistic design process.

13. What will happen to the results of the research project?
The data may appear in presentations and journal articles keeping at all times your anonymity.

14. Will I be recorded, and how will the recorded media be used?
The audio and video recordings of the interviews and design activities in which you may take part during this research will be used only for transcriptions and analysis. They are also going to be used for illustration

in conference presentations and lectures. In the case of images and videos, all faces will be blurred using a photo editing software so that participants are not identifiable. No other use will be made of them without your written permission, and no one outside the project will be allowed access to the original audio, video and image recordings.

15. Who is organising and funding the research?

This project is funded by the EPSRC and Cardiff University and is part of my PHD dissertation at the Welsh School of Architecture, Cardiff University.

15. Contact and further information:

Student:	Alicia Nahmad
E-mail:	nahmadvazqueza@cardiff.ac.uk
Address:	PGR Room, Welsh School of Architecture Bute Building, King Edward VII Avenue Cardiff, CF10 3NB Wales, United Kingdom

Thank you very much for taking the time to participate in this project. Your assistance in providing the required information will be highly appreciated.

APPENDIX F PARTICIPANT CONSENT FORM

Title of Research Project: *"A Framework for Robotic Assisted Design: Explorations of Industrial Robotics in Architectural Design"*

Name of Researcher: *Alicia Nahmad Vazquez*

Participant Identification Number for this project: _______

Please tick next to each statement as appropriate:

I confirm that I have read and understand the information sheet dated _________________ explaining the above research project
and I have had the opportunity to ask questions about the project.

I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. Also, should I not wish to answer any particular question or questions, I am free to decline.

I understand that my responses will be kept strictly confidential.

I give permission for members of the research team to have access to my anonymised responses. I understand that my name will not be linked to the research materials, and I will not be identified or identifiable in the report or reports that result from the research.

I agree with the data collected from me to be used in future research

I agree to take part in the above research project.

___________________________	_________________	______________________
Name of Participant	Date	Signature

APPENDIX G PARTICIPANT BACKGROUND FORM

Participant reference number: _________ Date: _______________

Sex:

Age:

Current year of study or years of graduate experience:

Do you have any prior experience interacting with industrial robot manipulators? YES / NO

Do you have any prior experience interacting with other forms of automation in your design workflow?

YES / NO

Which other form of digital fabrication tools have you used:

- Laser Cutter
- 3D printer
- CNC router
- CNC miller
- Other (specify which)

APPENDIX H THE CODING TEMPLATE

ANALYSIS OF THE CASE STUDIES

DESIGN BACKGROUND

Design Background - Not used to exploratory design
Design Background - Only does representational models
Design Background - Positive sentiment about working models
Design Background - Precious about physical models
Design Background - Trying to do more working models
Design Background - Uses models for form finding
Design Background - Yes working models

DESIGN ELEMENTS

Design Elements - Robot - Good for abstract designs
Design Elements - Software - Sentiment difficult
Design Elements - Software - Sentiment positive - excited
Design Elements - Software - Sentiment positive - guidance
Design Elements - Software - Sentiment time consuming
Design Elements - Workflow - Difficult to design the 2D rather than the 3D
Design Elements - Limitations for it to work properly with the robot / material
Design Experience - Would do everything same

EMOTIONAL RESPONSE

Emotional Response-Amazing
Emotional Response to Robot - Positive - Cool
Emotional Response to Robot - Positive - Exciting
Emotional Response to Robot - Positive - New toy
Emotional Response to Robot - Positive - Quite like it

EXTERNAL ELEMENTS

External Elements - Attribution of blame
External Elements - No reliable
External Elements - School - Limits access to the robot

HUMAN ELEMENTS

Human - Attribution of blame - We gave it the wrong tool/information
Human - Sentiment – Powerful
Human Elements Negative - Less strength
Human Experience - Difficult to translate design desires for robot to do
Human Mental Models - Not ready to incorporate robot thinking
Human Reliability - Low

CONTRIBUTION

Human Contribution - Negative - Told the robot the wrong things

Human Contribution - Negative - Too embedded to see the bigger picture
Human Contribution - Negative - Wrong path and simulation
Human Contribution - Positive - Tactile relation with materials

EXPERIENCE
Human Experience - Frustrating - Final form far from original design
Human Experience - Low
Human Experience - Mot enough to feel comfortable

IMPROVEMENT
Human Improvement - Better robotic understanding allowing more robot agency
Human Improvement - Design Improvement for material properties
Human Improvement - Design Improvement to increase robotic agency
Human Improvement - Design with a more 'robotic 'thinking
Human Improvement - Design with robot capabilities/movements in mind
Human Improvement - Jogging and understanding robot coordinates
Human Improvement - Make more tests / be more adventurous
Human Improvement - Not needed
Human Improvement - Test the boundary of the robots (more extreme design)

ROBOT ELEMENTS

Robot - Attribution of Blame - Not cutting as expected /missing /adding segments
Robot - Attribution of Credit - Did his job perfectly

Robot - Sentiment – Interesting
Robot - Sentiment – Negative
Robot - Sentiment – Neutral
Robot - Sentiment – Positive
Robot - Sentiment – Sad (it cannot feel)
Robot - Sentiment – Harder than expected

Robot – Safe Cooperation – Positive

Robot Use - Negative - Complex
Robot Use - Negative - Not Intuitive
Robot Use - Neutral - Practice required

Robot Motion - Positive - Doesn't hold back due to preconceptions
Robot Motion - Positive - Very controlled

Robot Elements - Desirable - If it could know more about the task
Robot Elements - Joints and Joint Limits- Negative sentiment

Robot Elements - End Effector - Limited functions (i.e. can't push up)
Robot Elements - End Effector - Needs to be designed (won't do something alone)
Robot Elements - End Effector - Kinect limitations
Robot Elements - End Effector - Negative - blade no reliable

Robot Elements - End Effector - Reliable
Robot Elements - End Effector - Test more options /tools

Robot Elements - Code - Sentiment constraining
Robot Elements - Code - Sentiment difficult

Robot Elements - Concerns - Brake without being intentional
Robot Elements - Concerns - Lock and cage / security items

Robot Elements - Negative - Need to plan in advance
Robot Elements - Negative - Accessibility
Robot Elements - Negative - Needs continuous direction/no autonomy
Robot Elements - Negative - Movement Range limits
Robot Elements - Negative - Narrow design space solutions (cannot do twisting, hanging, etc)
Robot Elements - Negative - Needs practice to use (more experience)
Robot Elements - Negative - Needs to consider specific robot motions in the design path
Robot Elements - Negative - Needs very precise information
Robot Elements - Negative - No awareness of surroundings
Robot Elements - Negative - No reliable
Robot Elements - Negative - Single way of acting
Robot Elements - Negative - Steep learning curve to be comfortable
Robot Elements - Negative - Stop button
Robot Elements - Negative - Tricky for experimentation
Robot Elements - Negative - Inadaptability / inflexible
Robot Elements - Negative - No creative
Robot Elements - Negative - Time Consuming to plan

Robot Elements - Positive- Enhances human action
Robot Elements - Positive- Increases knowledge of the material
Robot Elements - Positive- Manual manipulation to do what you want
Robot Elements - Positive- Quick
Robot Elements - Positive- Strong
Robot Elements - Positive - Can be trusted
Robot Elements - Positive - Efficient
Robot Elements - Positive - Encourages systematic thinking
Robot Elements - Positive - Endurance// doesn't get tired
Robot Elements - Positive - Its limitations push your design thinking
Robot Elements - Positive - Multiple uses/ things it can do
Robot Elements - Positive - Only has to be learnt once / high time investment but high rewards
Robot Elements - Positive - Precise / accurate
Robot Elements - Positive - Repeatability
Robot Elements - Positive - Stop button
Robot Elements - Positive - Surprise element
Robot Elements - Positive Feeling

Robot Elements - Teach pendant/ Communication - Not intuitive to use
Robot Elements - Trust - Performance

DESIGN PROCESS
Robot - Design Process - Better geometric understanding
Robot - Design Process - Better understanding of the digital world
Robot - Design Process - Iterate quicker
Robot - Design Process - Rigorous experimentation

APPEARANCE
Robot Appearance - Changes depending on the end effector
Robot Appearance - Colour – Pink
Robot Appearance - Colour – No good

Robot Appearance - Negative - Difficult to know which way it is looking
Robot Appearance - Negative - Heavy
Robot Appearance - Negative - Scary (razor end effector)

Robot Appearance - Positive
Robot Appearance - Positive - Adorable
Robot Appearance - Positive - Friendly (ball end effector)
Robot Appearance - Positive - Impressive
Robot Appearance - Positive – It does not move from the floor
Robot Appearance - Positive - Love talking to him
Robot Appearance - Positive – Size encouraging
Robot Appearance - Positive – Size compelling

CONTRIBUTION
Robot Contribution - Better at the end than for the exploration
Robot Contribution - Low (participant did not care to use the info)

Robot Contribution - Negative - Cannot push up
Robot Contribution - Negative - Digital Simulation was wrong
Robot Contribution - Negative - Machine limitations
Robot Contribution - Negative - Lack of sensors
Robot Contribution - Negative - Lack of tactile/ pressure sensors

Robot Contribution - Positive - Encourages Creativity
Robot Contribution - Positive - Accuracy
Robot Contribution - Positive - Alternative ways of exploring the material
Robot Contribution - Positive - Different viewing perspectives
Robot Contribution - Positive - Feedback
Robot Contribution - Positive - Forces to engage with the material outcome early on
Robot Contribution - Positive - Freedom to explore alternatives
Robot Contribution - Positive - It could do many different things
Robot Contribution - Positive - Matching digital and physical
Robot Contribution - Positive - Material information for future moves
Robot Contribution - Positive - More control over the deformation/material
Robot Contribution - Positive - Pushing Strength
Robot Contribution - Positive - Very good for this task

FEEDBACK
Robot Feedback - Accurate
Robot Feedback - Can be used for testing material conditions, etc
Robot Feedback - Confusing
Robot Feedback - New perspectives on the design
Robot Feedback - Noise on the information
Robot Feedback - Provides useful quantitative information
Robot Feedback - Reliable
Robot Feedback - Sentiment positive
Robot Feedback - Trying to match digital and physical
Robot Feedback - Useful

PERFORMANCE
Robot Performance - Accurate - Negative - moved external elements (frame)
Robot Performance - Negative - Non even performance
Robot Performance - Negative - Reaching motion limits
Robot Performance - Positive - Immediate stop when requested
Robot Performance - Reliable- Yes
Robot Performance - Reliable- Yes but with supervision

TASK

Task - Interaction with the Robot - Complex
Task - Interaction with the Robot – Positive - Adequate for the task
Task - Interaction with the Robot – Positive - Fun
Task - Interaction with the Robot – Positive - Nice
Task - Interaction with the Robot – Positive - Safe

Task - Positive - Expands your horizons about technology
Task - Positive - Interaction with the robot forces to think about design feasibility
Task - Positive - Interesting, enjoyable
Task - Positive - Learn new things including a robot
Task - Positive - Unique opportunity (experiment with robot)

Task - Robot Positive - Forces for systematic thinking
Task - Sentiment - Interesting
Task - Trust - More practice will increase trust
Task - Negative - Design takes most of the time that you spent with robot
Task - Negative - cannot do without help

Trust in Human Performance with the robot - Low
Trust in Robot Performance – Positive

APPENDIX I FULL INTERVIEW TRANSCRIPTS

WSA CASE STUDY

CS2-001 (Char)

A: [00:00:04] What do you think, regarding the robot arm and the design process. Yes. Are you ok... you don't want to?

CS2-001 (Char): [00:00:17] No no no.

A: [00:00:17] Is just for me to remember everything. It won't be transcribed is just for me to remember. What do you think that are the strengths and weaknesses of the robot, of a tool like the robot?

CS2-001 (Char): [00:00:28] Well it's quick. It's much quicker much stronger than what you'd normally be able to do it without material. And it allows you therefore to know what. The material constraints are very quickly. So, for me it's like working with the material. And kind of its almost like a Louis Kahn. Asking the brick what it wants to be. Here you are literally asking the concrete sheet how it wants to behave. In my case the head of the joint that jointed to the to the timber frame when it wants to break so is testing the extremities of the material in real time.

A: [00:01:23] Good. What do you think is the most kind of a challenging thing to overcome on using the robot arm? Like the weaknesses of the machine, of the robot, that you think are very challenging to overcome.

CS2-001 (Char): [00:01:38] The fact that it has one way of acting. It's a very narrow kind of. This is what it can do. So, if I was doing this by hand, I'd probably concentrate on doing different things to it. I wouldn't just push I Kind of maybe twist it I'd like maybe tight ropes around the corners to kind of put them up and the robotic arm can't make knots. It's Strong but in only one capacity.

A: [00:02:16] No. That's true. I mean absolutely, but depends actually but yeah, I mean. You have to design on a balance if you want him to tie something then you have to design something to tie up. Yeah. Is there anything that after doing the exercise, well, maybe you are actually because you said if you can do it again.... Is there anything that you might have changed on your initial approach now that you did it.

CS2-001 (Char): [00:02:37] Yeah, now that I know how the material works. I would probably design it; I would make the distances between the cuts in a more informed way. When I was doing it, the aim was kind of test how these cuts would work and how the horns would work as well. But now that I know, I would obviously make it more informed and more bespoke to what my design intent is.

A: [00:03:10] Is there anything that you would do on the same way?

CS2-001 (Char): [00:03:14] I would.... I keep the horns.

A: [00:03:19] They look very good actually, and they came out very long. I wasn't expecting them to kind of hang so much.

CS2-001 (Char): [00:03:24] No I wasn't. I wasn't a fan of them but I though you know I really want to see how it works.

A: [00:03:30] They are very funny. Do you think that the robot can aid your creative process?

CS2-001 (Char): [00:03:40] I think. Yes. Yes, it can. It can do that by giving. Well what I said by giving information about the capacity of the material that I'm working with. So, if I were to do it with my own hands, I probably would be timid with how I push into the sheet. But then I would have a more tactile relationship with the materials. I would treat it more like, as though I could break it. Yeah. That it doesn't have a kind of sensor. It doesn't have that kind of sensibility. Yeah. So, it's a lot more, it's a lot more abrupt. But in a kind of, I suppose it can be used in a bad way. But I think in this exercise it was a good thing to do for this way of designing, because you're the designer and you're using that as a tool. It's a good way of exploring the materials durability. With - under the different forces and different conditions.

A: [00:04:52] Do you normally what I mean do you do physical models or did you use to do physical models throughout the design or only at the end?

CS2-001 (Char): [00:04:59] Throughout the design.

A: [00:05:01] Do you think that's better than people that does them only at the end?

CS2-001 (Char): [00:05:04] Yes, Absolutely. I think the representation of the design is important to show to the client but in the design process you have to have them throughout the design. It's a work in progress. Okay.

A: [00:05:19] Do you think that the information that the robot was giving you, by the robot I mean the scanning. Did that actually help you with the material or on informing the design or on understanding anything at all?

CS2-001 (Char): [00:05:32] Yeah. I think it was a different way of looking at it, and that always helps to distance yourself from the process. So, when I was looking at the physical thing from above and from the side that's awesome for me, but it was a different way of doing the same thing. So, it's kind of gave me a different perspective on what I was doing. And I think in a more detailed way as well. Because there was a lot more. .... You Know this is this is how much has changed. Whereas if I was looking at it, I was so deep in the process that I couldn't withdraw myself from it enough to see: this horn is actually in the same place. I didn't know that. So

A: [00:06:22] That's very interesting. But that's true actually I did. That's very much interesting. It does help to distance and to see it more quantitatively, what is happening.

CS2-001 (Char): [00:06:29] Yeah that's true. Yeah.

A: [00:06:33] You already said what you would design differently.

CS2-001 (Char): [00:06:34] Should I say it allows you to see the process in a more quantitative way.

A: [00:06:39] That's what it was. Yeah. Thank you. There's a quote.

CS2-001 (Char): [00:06:47] Reference in A.

A: [00:06:55] Can you say what were your first thoughts, not today maybe, but on the first time about working with the robot or did you expect it to be this way?

CS2-001 (Char): [00:07:03] No I didn't. I didn't. Oh God what I expect, I just thought it was cool, you know. Because You're working with something that not a lot of people have worked with before. So, it was exciting. And then it was just it was like a new toy. It was, was fun.

A: [00:07:22] Do you think you can rely on the robot to do; I mean whatever he had to do was it going to be performed reliably?

CS2-001 (Char): [00:07:30] What I have to for it to be a viable tool, I'd have to have more practice with it. To learn how to use it properly. The movements that I made just sometimes up and down went down again. Yeah. That is because I didn't remember where I was, X Y and Z. It's kind of that I have to think about it's not intuitive as of yet. But I don't know. I also question I'd have to learn how to use it properly...

A: [00:08:00] To trust him? Or would you trust him that whatever... would you trust that if he has to cut, he will cut and if he has to push, he will push.

CS2-001 (Char): [00:08:02] Oh Yeah, yeah. It's definitely that I can rely on obviously if it only takes two months. It's like it's like a craft knife. It will do whatever you want to do. But I don't know. I think the problem lies with the translation of my thoughts into the movements of the machine. The interface is just not.... It's very well designed but it’s not very well presented. I don't think. It has that kind of thing to hold, and that it's just too hard... No, it's. This is awkward isn't it.

A: [00:08:45] I agree fully. The appearance of the robot influenced at all how you feel about the robot? Not really, he could look like whatever?

CS2-001 (Char): [00:08:53] Well not, it's. It's depressive.

A: [00:08:59] Depressive?

CS2-001 (Char): [00:08:59] I Think it is. It's kind of well you know it's big, and that's what makes it impressive.

A: [00:09:06] Impressive. I thought you said depressive.

CS2-001 (Char): [00:09:08] No. The only thing that I would change maybe is the colour. That's just the.... That's the design. I don't think it has to be a photo. I don't think. So, It's just big. And that's that makes it. More compelling to use it. Yeah.

A: [00:09:28] Yeah. That's quite interesting, I always thought that the smaller robots were more compelling to use.

CS2-001 (Char): [00:09:32] I haven't used the smaller robots here. Maybe. If I had. But maybe it's a Freudian thing.

A: [00:09:42] That's okay.

CS2-001 (Char): [00:09:47] I just gave a lecture. We could go about. You know if someone wants to own a car a very long car. That's a Freudian metaphor for a different need.

A: [00:10:04] Interesting. Thanks a lot! The only thing is not to use like your name. I would tell you the number and if you can just answer this questionnaire here.

CS2-001 (Char): [00:10:18] Yes you are.

CS2-002 (Nik)

CS2-002 (Nik): [00:00:00] I think that they would look like rawer, like natural with the grey colour

A: [00:00:04] Yeah, then maybe I can put them like in a frame or something, and.

CS2-002 (Nik): [00:00:10] Yeah.

A: [00:00:10] I mean some of them are nice, are very nice.

CS2-002 (Nik): [00:00:13] Some of them yeah, the ones that are still hanging. I mean the ones, the second one there is good.

A: [00:00:19] I think that's CS2-006(Jac)

CS2-002 (Nik): [00:00:20] It's good.

A: [00:00:20] A lot are very nice. I like, I like. I like quiet a lot actually.

CS2-002 (Nik): [00:00:30] Yeah.

A: [00:00:30] Let's see how yours comes out.

CS2-002 (Nik): [00:00:32] Yeah, would see.

A: [00:00:34] So, just like some quick questions.

CS2-002 (Nik): [00:00:37] Okay.

A: [00:00:37] So what do you think are the kind of strengths and weaknesses of the robot arm? Or a tool like a robot?

CS2-002 (Nik): [00:00:46] Yeah, it helps you like prioritize everything and like make sure that you are programming it in the right way that it should be done. Bu the weaknesses I think that you should like think forward. For like challenges that can go to the limits of its movement.

A: [00:01:16] So, the movements are a challenge?

CS2-002 (Nik): [00:01:18] Yeah.

A: [00:01:19] What do you think was the most challenging, challenging part of the robot? Or the most difficult one to overcome?

CS2-002 (Nik): [00:01:27] Maybe playing with it and moving it, I think. Like for me without actually him thinking that I'm in a panic.

A: [00:01:37] You were pretty good at the end.

CS2-002 (Nik): [00:01:40] Yeah. Today. Yeah. But before that.

A: [00:01:44] Is there anything that you learn now that you did the task that might have change how did you initially approached it?

CS2-002 (Nik): [00:01:50] I wouldn't have done the curves in the way I did them. I would have created a more dramatic form. Yeah. I mean the way we use the robotic arm or the way the robot is existing? I don't know. I think I would try to design some things so that I can think of a way in which it could be done by robotic arm

A: [00:02:19] But now, now you know what the robot can do in a way.

CS2-002 (Nik): [00:02:22] Yeah, I mean I know how he does it so...

A: [00:02:26] Perfect. Do you think that the robot actually helps can help you in the creative process? I mean now that you're thinking how to do something.

CS2-002 (Nik): [00:02:33] Definitely. Yeah.

A: [00:02:35] Yeah? Do you think that it can maybe be an obstacle in the creative process?

CS2-002 (Nik): [00:02:40] I think no if you know how to...Like, because we had challenges with the code. If I know how to overcome that then I don't think that it would be an obstacle.

A: [00:02:51] Was there anything that you were hoping to achieve that you couldn't?

CS2-002 (Nik): [00:02:56] Yeah, I mean if I'm about to do it again, I would do a different shape. Like a different shell. With bigger curves and not in the same area so that it can push further and further. Yeah. I mean, I got the point of what is the end result of it.

A: [00:03:20] Do you normally do models, like do you normally are doing working models or do you only do models at the end of the of the design?

CS2-002 (Nik): [00:03:26] Last year I did it at the end of it, but this year I am trying to do working models and see if that helps.

A: [00:03:27] Do you think that the scanning, that the robot that the information the robot was giving you was useful?

CS2-002 (Nik): [00:03:37] With my shape, not that much because it wasn't shaped, like it wasn't going back. Like that woks that much. But yeah and he... if it wasn't the shape, I mean ours was pretty much flat.

A: [00:03:55] What about in understanding how the material performs?

CS2-002 (Nik): [00:03:58] Yeah, I mean I got the process of how the scanning can be good for the next move that I do with the robot

A: [00:04:06] So it informed the next move, basically.

CS2-002 (Nik): [00:04:06] Yeah.

A: [00:04:06] Do you think that the robot was accurate in doing that in in pushing and cutting?

CS2-002 (Nik): [00:04:12] Yeah, if it didn't move the frame, to one direction, Yeah.

A: [00:04:20] You said that you feel that the robot was reliable?

CS2-002 (Nik): [00:04:28] Yeah.

A: [00:04:32] Is there anything that that make you uncomfortable about the robot? Like do you think that if it looked differently or ... would be better or something?

CS2-002 (Nik): [00:04:42] The way in which it reaches its limits that then you have to move it home so that it can return to zero degrees...

A: [00:04:49] Oh winding you mean...

CS2-002 (Nik): [00:04:51] Yeah, yeah.

A: [00:04:52] That you found annoying or.

CS2-002 (Nik): [00:04:54] Well, yeah like the whole movement, then when it reaches the limit you have to put it in the direction in which it's going to retreat from, like zero degrees to...

A: [00:05:05] I mean that's because they cannot they cannot keep going they wind up.

CS2-002 (Nik): [00:05:07] The thing is that not all of the arms rotate like 360 degrees. I. Love.

A: [00:05:15] All of them do 360.

CS2-002 (Nik): [00:05:17] Well, I mean like the robot when it reaches its limits you have to...

A: [00:05:20] You have to get him back to zero 360.

CS2-002 (Nik): [00:05:23] Yeah.

A: [00:05:25] Is there anything that encourage you to trust the robot? Or that makes you, that makes you concerned about interacting with the robot?

CS2-002 (Nik): [00:05:34] Yeah, the thing that it thinks that I'm in a panic mode. Yeah, its reliant. I don't think that there are any obstacles that make you feel stressed about it.

A: [00:05:45] You managed pretty good at the end like you were a lot smoother on your moves.

CS2-002 (Nik): [00:05:49] Yeah, I was trying.

A: [00:05:49] No a lot, like really a lot. Perfect. Thank you so much. And I hope you can answer this questionnaire. Its multiple option. Don't put your name, I give you the number and I give you a pen here.

A: [00:06:01] Did you have fun?

CS2-002 (Nik): [00:06:01] Yeah, seriously.

CS2-003(Val)

A: [00:00:02] Why do you think he is good for you?

CS2-003 (Val): [00:00:04] He is precise and fast.

A: [00:00:05] What?

CS2-003 (Val): [00:00:05] It's precise and it's fast.

A: [00:00:09] What do you think is the weakest part of the robot?

CS2-003 (Val): [00:00:13] That it can't really adapt.

A: [00:00:16] Did you learn anything on this process?

CS2-003 (Val): [00:00:20] Yeah.

A: [00:00:20] What did you learn?

CS2-003 (Val): [00:00:20] I learned how to move a robot.

A: [00:00:21] What about your design? Did you learn anything about your design process?

CS2-003 (Val): [00:00:36] I just learned that designing takes up to ninety five percent of the time you spent with the robot.

A: [00:00:41] But do you think it helped you in your in your design process at all? To know that you were going to use a robot at the end?

CS2-003 (Val): [00:00:59] Yeah, kind of forces you to be more precise. Whereas if you like make the robot cut pieces of paper you don't really need to measure everything up, you can kind of just see. Whereas here you have to know or stuff like this happens where like part of it breaks.

A: [00:01:17] Yeah. What was the more confusing or challenging part of using the robot?

CS2-003 (Val): [00:01:26] Predicting the outcome, even though that shouldn't be the case.

A: [00:01:30] Predicting the outcome?

CS2-003 (Val): [00:01:30] Yeah. In the sense that like is it really feasible what you design on the computer?

A: [00:01:40] So you think that the robot put you a lot of limits in what you could do?

CS2-003 (Val): [00:01:46] I think it did.

A: [00:01:46] Yeah. What do you think you could, you would need to know to do no longer have these limits?

CS2-003 (Val): [00:01:55] I had to spend so much time on the process part that... You know that it cuts fast but to get it to start cutting, like all the stages before makes it not as worth it. Like it makes me think maybe I should just use an exacto and just keep going like seven times. Will I have all of these problems.

A: [00:02:23] Yeah but after you saw the pushing you decided to change everything though, you just wanted to keep pushing.

CS2-003 (Val): [00:02:29] Yeah, I mean what was the question again?

A: [00:02:37] No, just talking about what do you think are the limitations of the robot. Not any question.

CS2-003 (Val): [00:02:43] I think It's not a limitation but more issue that it can actually make you do more because you can start playing with it, see if he kind of go in a path and do what you want to do with versus just write a program and then see if it predicts correctly what would happen in real life.

A: [00:03:01] So what do you mean, so was it good to use the robot or not?

CS2-003 (Val): [00:03:04] I mean in some ways it is, like if you use material that isn't conventional and you can't really use like human manpower, or you want it to stay in place for a long time then it's useful. Is like this third hand.

A: [00:03:19] Yeah.

CS2-003 (Val): [00:03:20] Versus like becoming a primary hand for you to use.

A: [00:03:26] What about the robot? What do you think? Do you think it looks friendly or scary?

CS2-003 (Val): [00:03:30] When it has a razor it looks scary. When it has the balls friendly.

A: [00:03:35] OK. Good to know. Good. Do you think it can give you information back? I mean what did you think was better? Do you think scanning is useful or not really?

CS2-003 (Val): [00:03:48] If you want accuracy, I think it would be very useful, but I'm just playing around that is why is not very useful right now.

A: [00:03:59] Do you trust the robot? Do You think that he will do what you want him to do?

CS2-003 (Val): [00:04:03] I haven't seen him not do what I want it to do.

A: [00:04:06] So you trust him to do what you want him to do?

CS2-003 (Val): [00:04:08] Yeah, I think it is not smart enough to learn how to hit people.

A: [00:04:14] Cool, thank you.

CS2-004(Epa)

A: [00:00:03] What do you think. Was kind of the strengths.... Did you enjoy using the robot arm to start with?

CS2-004 (Epa): [00:00:04] Yeah, it was fun, was fun.

A: [00:00:08] What do you think was.... Do you think there was any strength in working with a robot arm, anything that the robot gave you that you couldn't have without the robot arm?

CS2-004 (Epa): [00:00:24] I think.... It gives you more precision but at the same time is a bit not difficult but maybe complicated to do, at least with the points that has to cut. So, I don't know. Am I clear?

A: [00:00:43] Not really...

CS2-004 (Epa): [00:00:45] So, even though it can cut something with precision, which is a good thing. Instead of cutting with the hand or you could use a different material to do that. When we did it in Maya you have to put something. you have to put some points that the robot cannot pass. That was like the difficult part or the complicated part of ... so, let’s say is more precise to cut...

A: [00:01:12] Ok, so what do you think are the weaknesses of the robot? That it’s too complicated?

CS2-004 (Epa): [00:01:16] Maybe the part of making the points. But I think.... making the points where it has to cut.

A: [00:01:22] I mean do you think that doing this, like what you were doing today and this stuff, made you learn anything? that I mean if you were to design this again, would you change your way of thinking about it?

CS2-004 (Epa): [00:01:47] Yeah, I think so. I mean as you see now with the cuts. It could have been, I don't know.... If I was to design it, I might change somehow to make something, I am not sure what exactly but I might have done something differently in terms of the project proportion there.

A: [00:02:15] Do you think the robot arm can help your creative process? Or does it make your creative process more difficult?

CS2-004 (Epa): [00:02:26] I think for starters. For some of us to do it for the first time is a bit time consuming. To understand like for me know. To understand how it works and with the files, and to do the robot path then. This, I think it takes some time but definitely for someone who is more experienced with it. It might be easier. It might be a more creative platform.

A: [00:02:53] Was there any stuff about the robot that you thought was confusing or limiting?

CS2-004 (Epa): [00:02:59] Not really, I mean the difficult part was the one where we used Maya but I already said that.

A: [00:03:08] But was there anything that you thought you wanted to do and you couldn't achieve, and you couldn't do because of the robot? Because the way the robot is, or moves or something?

CS2-004 (Epa): [00:03:16] No. I don't think so.

A: [00:03:17] No. Cool. Do you like to do physical models?

CS2-004 (Epa): [00:03:29] Well, yeah, I enjoy it. I enjoy it during the final project

A: [00:03:33] Just at the end? Not through the process but just at the end?

CS2-004 (Epa): [00:03:34] Yeah, at the end.

A: [00:03:35] Do you think that scanning and the information from the robot, did that help you at all?

CS2-004 (Epa): [00:03:49] I will say so much so

A: [00:03:51] Like seeing here the information of how the physical model relates to the digital model, does that help you at all? Or not really?

CS2-004 (Epa): [00:03:57] Well helps, but still if it’s a (thinking) yeah it helps. No, I was thinking that if you have something in mind. I mean is there is something. The final project is a bit far from the design that it might be a bit yeah frustrating.

A: [00:04:23] When you started to push the fabric and you had an idea. When you saw how it was working, did you change what you wanted to do? Did it change your idea?

CS2-004 (Epa): [00:04:31] The Design?

A: [00:04:35] Now that you were pushing after seeing and after the first pictures that we took. Did it change your idea of how it could look? like seeing the results that were emerging?

CS2-004 (Epa): [00:04:42] Perhaps, a bit limited but yeah.

A: [00:04:42] Did you like to interact with the robot?

CS2-004 (Epa): [00:05:05] yeah, it was fun.

A: [00:05:05] What did you feel about the robot in general?

CS2-004 (Epa): [00:05:06] It was fun, like watching it rip and cut. But had to be more experienced to be like enjoying it. And to have the fun of making something that it's nice and you know...

A: [00:05:15] Do you feel that you can rely on him? That he would do the stuff that you want him to do like precisely?

CS2-004 (Epa): [00:05:28] Well, I think so.

A: [00:05:31] You think he will do whatever you tell him precisely?

CS2-004 (Epa): [00:05:34] I think, perhaps. I mean it's the first time. I have never interacted with robotic arm before, never before, so I am not sure.

A: [00:05:42] Do you think if the robot looked different, will it be easier to work with him? Like the appearance or like how it moves? Is there anything about the robot that actually makes you feel uncomfortable or makes you think that it will make you feel better about him if he was different in any way?

CS2-004 (Epa): [00:06:00] No, I mean. You can see different ways.

A: [00:06:05] He's OK for you?

CS2-004 (Epa): [00:06:06] Yes, he is OK.

A: [00:06:09] Did you have any concerns when you were working with the robot? Or when you were playing the programs or moving him around?

CS2-004 (Epa): [00:06:19] Maybe the fact that sometimes is not the emergency move but might be that stops it, like you move it and then suddenly stops.

A: [00:06:29] Oh the break.

CS2-004 (Epa): [00:06:29] Yeah, the break.

A: [00:06:37] Cool, thank you. If you can just answer this, is a multiple option questionnaire.

CS2-005(Sim), CS2-018(Bart) and CS2-026(Gian)

A: [00:00:00] You didn't use it before anyway.

CS2-005 (Sim): [00:00:08] I think is really interesting like you could do a lot of things with it. Obviously in two sessions there's a lot to take in and there's a lot to learn. I think we would have to like... I Know I'm just going to forget them very quickly. Because you need to keep practicing things to remember.

CS2-026 (Gian): [00:00:27] I think it was just not to learn but to have an idea about what's going on because it was only, the first session was about the Maya thing and then it was only one session about the robot and then we had to fabricate it. So, it was fine, I mean we have an idea how things work we don't know how to do that by ourselves... Yeah.

CS2-005 (Sim): [00:00:50] But I think there's really just learning all of these things and all the different... Like there's so much that you can do with technology, but we don't never explore it.

A: [00:01:03] Well yeah is good that you explore a little bit.

CS2-005 (Sim): [00:01:05] No, as in usually we don't, so it was nice to come to this session and learn things that I would have never been able to see what a robot does if I haven't done this

A: [00:01:17] Good to know.

CS2-005 (Sim): [00:01:19] Yeah, it's really interesting, I enjoyed it.

A: [00:01:24] What do you think, was a strength or something that you can maybe in the future apply by using a robot arm. Do you think there's any kind of weaknesses of the robot and specific strengths? Or not?

CS2-026 (Gian): [00:01:39] The weaknesses maybe are that when you fabricate something by yourself you do it exactly as you want, but when the robot does it. And because the robot isn't... Is just a robot, it doesn't know that it might destroy something so you might like sometimes it doesn't do exactly what you want, but its quicker with the robot so...

A: [00:02:10] What about when it is scanning and kind of knowing more or less about things, do you feel that that kind of maybe makes him know something?

CS2-005 (Sim): [00:02:23] I think the scanning thing is probably one of the best things about the robot so that you can see the variation between your like digital explorations and what actually happens in the real world. And being able to see them side by side. And the points that match and the points that not match. Like gives you an idea of, I don't know, maybe you can investigate the factors of why your physical model was different from whatever you did digitally.

A: [00:02:55] You're thinking it like when you are designing it can help you to like, yeah. That's some very interesting. Nice. What was the more challenging or confusing thing that you felt about the whole...? I mean I know it was a fast thing. It was only three day. But what was the more confusing or challenging bit?

CS2-026 (Gian): [00:03:17] I think to do the curves.

A: [00:03:18] The what?

CS2-026 (Gian): [00:03:19] To do the curves on Maya, that was difficult.

CS2-018 (Bart): [00:03:21] Yeah.

CS2-005 (Sim): [00:03:24] Yeah. Because I think that when we're designing like in our design projects, we design the finished product whereas for this one we were designing something in the beginning and we didn't know how it would turn out. We were trying to make something which looked good but when it deforms you know you don't know how it's going to look like.

A: [00:03:46] Is like designing the parameters and the potential of the system. Is there anything that you wanted to do and you think the robot was limiting you? Do you think the robot, because the robot has limitations, you could then do about your design at all?

CS2-005 (Sim): [00:04:03] Well, when I first made the curves that I made initially, I don't know if you remember, when it was, like that kind of... Do you remember? I didn't have many things on the edge of the square. Maybe not necessarily but it's like the more the simpler you keep your like. There are certain limitations to ensure that your thing like works properly. For example, like CS2-018 (Bart) thing, it was quite complex and then, because, you can't exactly control it maybe. Because if you're doing it yourself like you push and you can feel like whether it's going to break or not, but with the robot you have to limit yourself to certain things like curvature, cut time.

A: [00:05:20] Thank you. We were just talking about what were the limitations that you think the robot put into the process? And CS2-005 (Sim) was expanding on this.

CS2-018 (Bart): [00:05:34] It's quite precise but it's quite difficult to control it. If you know what I mean. When you do it you have more control over the cutting of the curves

A: [00:05:45] You two guys agreed totally, that is exactly what CS2-005 (Sim) was describing, No, but I think that what you were saying was very interesting. That when you are pushing you can feel the force whereas the robot will just break it. A little bit actually, not too much. Do you normally do physical models when you are designing? Like through the design or you only do them like by the end of your design process?

CS2-005 (Sim): [00:06:09] It depend, sometimes we use the model to inform our design. I know that you do that a lot, don't you? (Pointing to CS2-026 (Gian))

CS2-026 (Gian): [00:06:13] Yeah, I do like a hundred models. I mean I keep doing models to discover and make the spaces, I'm creative but if I don't see them in 3-D I can't really understand.

A: [00:06:25] What about you?

CS2-018 (Bart): [00:06:27] I try to do models as well. Just to see how it looks like in three dimensions.

CS2-005 (Sim): [00:06:33] I think, I do models at the end, after I do my design.

A: [00:06:37] Okay, and you think it's better to do them at the end once the design is finished? Or you would prefer to do them...

CS2-005 (Sim): [00:06:43] Well, because I use things like where you model it 3D on the computer, so then I can very quickly change. Like, you look at the inside and you decide what you want the experience inside to be and you decide to change things. Whereas I feel like in a model I would be hesitant to change stuff once I've done it.

A: [00:07:02] What about when you need information? Like here, that the robot was scanning and telling you how was it similar to your mode... If you are using this.... Do you think that information is useful at all? And the information about how the material is actually deforming respect to what you thought it would happen.

CS2-018 (Bart): [00:07:20] Yeah.

CS2-005 (Sim): [00:07:20] Yeah, it does make a difference, the thing is, I don't know if it relates as much but I mean like the materially materiality of your building, maybe. If you've very like harsh weather conditions. You don't think it would... Like you probably don't think it would affect your building and then maybe in reality it does.

CS2-026 (Gian): [00:07:49] So you simulate like hard, like harsh conditions as well, Okay. Okay. Well, then the robot won't really simulate that.

CS2-005 (Sim): [00:07:55] It can push it until it breaks.

A: [00:08:00] Yeah, it can. They use them a lot for that actually, in the research group of Phillip Block it pushes until it breaks and they can be measuring the pressure where it is happening. Yeah that's a very physical thing. Did you have any concerns about the robot when you were working with it? Or moving it around?

CS2-005 (Sim): [00:08:26] This locking thing is very annoying, the whole security thing.

CS2-018 (Bart): [00:08:28] Yeah.

A: [00:08:28] Did you think that the robot was going to do his stuff reliable? Like pushing and cutting. Do you think he's kind of ok doing his work?

CS2-018 (Bart): [00:08:45] I think it's been proved.

A: [00:08:47] Yeah how?

CS2-018 (Bart): [00:08:49] I don't know how but I think it like, for example when you do like really small parts for example in my case those curves. Sometimes they were quite close to each other, and sometimes it didn't see that there is a small segment that shouldn't be cut and it cut it.

A: [00:09:14] So it should have some kind of feedback when it is cutting also. Have vision. Okay. Yeah. I mean. Yeah. Good. That's interesting.

CS2-018 (Bart): [00:09:22] And some cuts weren't really cut either. We had to cut them again.

A: [00:09:28] That's true. Yeah. Yeah.

CS2-005 (Sim): [00:09:37] Does that always happen with all the robots? Or is it because...

A: [00:09:40] No this one is in an angle. It's just because a building is an old building and the way it got installed.

CS2-005 (Sim): [00:09:53] But it makes a difference.

A: [00:09:55] Because when it is cutting, like this even if you want to draw a line on this end of the table it would draw a line and if you draw a line like this it will do like this. I mean if you have a piece of paper and a pen you will see that at the end it's not touching it's like millimetres but it makes a big difference. I mean that's something I was like. I mean some of the complications of having robots like in construction sites or stuff is because they really need everything to be super precise like when they work in factories. I mean the floor is levelled; everything is level like to the micromillimeter almost. Because they are super-duper precise so some of the problems is that they cannot deal with imprecision at all. So that's why it doesn't cut on the top. If I put him to go lower then it will be breaking the knife on the curves that are at the back because it will go too long. I have to maybe change the way I put the curves. So that these ones are lower and these ones are higher. I have to figure out something.

CS2-018 (Bart): [00:10:54] Yeah, they are pretty precise but they lack this human intuition when you can see actually when something will break probably you feel how much you should push and they don't have it. We as humans we can see and we can feel.

CS2-005 (Sim): [00:11:12] Things even like the human intuition thing is a big thing like in the middle of doing the curves for example you might decide that okay this side looks good. I want to do the same thing on the other side but obviously the robots don't understand stuff like that. You would have to have a very defined sense of what you want to do before you make the robot do it, and then there's not much really way for change.

A: [00:11:37] What about like when he is scanning and you can be pushing the material differently, maybe is different. Or maybe different from what you expected in the simulation but you kept pushing to make it lower anyway. Because I don't know maybe you like it lower. Because you kept pushing away and I mean when we were scanning, I told you like is already way lower than the Maya. I'm just asking do you think it kind of maybe also gave you the freedom to maybe change your design half-way through rather than if you only fabricate the final model you might get less pushing. Does that make sense?

CS2-005 (Sim): [00:12:10] Yeah it does.

A: [00:12:10] I don't know if it makes a difference like that in a way.

CS2-005 (Sim): [00:12:16] But then in another sense it is also like a lot more efficient than we would be.

CS2-018 (Bart): [00:12:20] Yeah.

CS2-005 (Sim): [00:12:20] Like for us to cut the concrete we had to keep doing it whereas it just went shshshs and done.

A: [00:12:28] Yeah, he is a heavy guy.

A: [00:12:30] And any thoughts? Any other thoughts. I think that's my questions.

A: [00:12:37] Just something, Did the appearance... Did the way it looks make you feel anything? Like do you think if he looked differently you might maybe trust him more and be happier about him, unhappy or less trustable, or something?

CS2-018 (Bart): [00:12:53] Maybe, it wouldn't need to be that heavy.

A: [00:12:57] If you what?

CS2-018 (Bart): [00:12:58] If It wouldn't be that heavy, maybe.

A: [00:13:01] Not that heavy, okay.

CS2-005 (Sim): [00:13:03] I think the fact that he doesn't move from his position on the floor, is a lot less scary.

CS2-018 (Bart): [00:13:10] Yes.

CS2-005 (Sim): [00:13:10] Like when I think robot you know when you see in TV and everything, they move around. If it moved, I would be very scared.

CS2-005 (Sim): [00:13:17] That's a very good point. Like what if you just sit back and be happy.

A: [00:13:23] And he comes chasing you.... Good. Thank you very much. I just need you to answer like some questions, just multiple options and then that's it. Yeah.

CS2-006(Jac)

A: [00:00:02] Did you enjoy the task?

CS2-006 (Jac): [00:00:05] Yes, I am sure.

A: [00:00:07] What did you feel were the strengths and the weaknesses of working with the robot arm?

CS2-006 (Jac): [00:00:14] Weaknesses.... I think the biggest weakness was the amount of time that the process takes. I told you last time being efficient in my design work, I don't know, if I would use the robot on my own. If I would be able to spend this much time on it. Probably if I get more efficient it would definitely could be more useful.

A: [00:00:45] Did you learn something now that you did the task that might help change how you initially approached it?

CS2-006 (Jac): [00:00:51] No.

A: [00:01:03] Would you have done everything on the exact same way?

CS2-006 (Jac): [00:01:03] I don't think so, probably.

A: [00:01:06] Do you think that the robot can help you in your creative process or on your design process?

CS2-006 (Jac): [00:01:13] Definitely. As I said I would have to spend much more time on it just to be...Just for it to feel more natural for me, I guess.

A: [00:01:30] So do you think that it obstructed your design process somehow or put limitations to it?

CS2-006 (Jac): [00:01:35] No. Not really, just because well it was the first task I have ever done. I guess it was.

A: [00:01:42] What did you think was the more challenging stuff?

CS2-006 (Jac): [00:01:49] I still don't exactly know how would I do things on my own.

A: [00:01:56] OK. So that's only practice.

CS2-006 (Jac): [00:01:57] Um yeah.

A: [00:01:58] Okay. Do you normally do physical models during your design process?

CS2-006 (Jac): [00:02:01] Yes.

A: [00:02:04] All the time or only at the end?

CS2-006 (Jac): [00:02:06] Most of the time. Yeah

A: [00:02:08] So, you do them throughout the process?

CS2-006 (Jac): [00:02:10] Yeah, I try to use them as form-finding or just as a tool.

A: [00:02:17] Do you think that the information that the robot gave you, did that help you to understand the material?

CS2-006 (Jac): [00:02:28] I don't know if the material, but I think that the comparison between the digital and the real was extremely interesting.

A: [00:02:37] Do you think that information might help your design?

CS2-006 (Jac): [00:02:41] Yes.

A: [00:02:42] The information that the robot is giving you.

CS2-006 (Jac): [00:02:44] Definitely.

A: [00:02:47] Did you change your design after seeing how it was deforming? or did you consider your original relaxed shape at all?

CS2-006 (Jac): [00:03:01] Well the material doesn't matter for me right now so I guess I was trying to get to the same form without any change.

A: [00:03:11] You think you can trust the robot? Did you feel that it was doing whatever it had to do, do you feel that it did it efficiently and correctly?

CS2-006 (Jac): [00:03:17] Yes, yes.

A: [00:03:19] Do you think that you can rely on the robot to do whatever its tasks, like cutting, pushing, etc?

CS2-006 (Jac): [00:03:25] Yeah.

A: [00:03:26] Okay. Is there anything about how the robot looks that influences how do you feel about it?

CS2-006 (Jac): [00:03:31] No definitely not. No.

A: [00:03:34] Okay. Is there anything that worries you about the robot? About interacting with him?

CS2-006 (Jac): [00:03:41] No.

A: [00:03:41] Do you trust the robot?

CS2-006 (Jac): [00:03:44] Yeah. For as much as I understand it, yeah.

A: [00:03:48] Is there anything else about it that maybe made you trust it more or made you distrust it somehow?

CS2-006 (Jac): [00:04:00] I think in terms of trust, that it is a practice will give me more trust, or maybe not trust but intuitive understanding I say.

A: [00:04:16] Thank you, thank you so much. I think you did a great job actually and you did improve dramatically, it was good... If you can only answer this multiple option questionnaire. Don't put your name I give you a number now and then we're done.

CS2-007(Chen)

A: [00:00:07] What did you feel were the strengths and the weaknesses of working with the robot arm?

CS2-007 (Chen): [00:00:14] Strengths are that the motions are very controlled, weaknesses that it is inflexible.

A: [00:00:45] Did you learn something now that you did the task that might help change how you initially approached it?

CS2-007 (Chen): [00:00:51] To consider more the way the robot arm works and moves on my design.

A: [00:01:03] Were there things that you were hoping to achieve that you couldn't because of the limits of the tool?

CS2-007 (Chen): [00:01:03] Some more sharp curvature that could not be cut.

A: [00:01:06] What would have been required to get around these limits?

CS2-007 (Chen): [00:01:13] I would test more cutting tools and more options for cutting to be able to cut sharper edges. Next time I would experiment more with the end effector.

A: [00:01:30] Can you talk about your first thoughts regarding interaction and working with a robot arm?

CS2-007 (Chen): [00:01:35] I though interesting, I want to see how can it work.

A: [00:01:42] How did the appearance of the robot influence your trust?

CS2-007 (Chen): [00:01:49] The appearance influenced me on my design approach. When I try to design something with robot arm, I should think the ways it will approach it and the ways I want to approach it and then find a suitable way to do that.

A: [00:02:16] Thank you, thank you so much. I think you did a great job, and spent a lot of time fine-tuning and jogging. You became very comfortable with the robot. I hope you come to use it again. If you can only answer this multiple option questionnaire.

CS2-009(Vel) and CS2-012(Ele)

A: [00:00:00] Is just for me to not forget what you say because you say a lot of interesting stuff. So, did you have fun with the experience?

CS2-012 (Ele): [00:00:09] Yes.

CS2-009 (Vel): [00:00:10] Yeah.

A: [00:00:10] Cool. So, what do you think are kind of the strengths and weaknesses of the robot?

CS2-009 (Vel): [00:00:19] I would say the strengths...All the opportunities that it gives you although accuracy was the first thing. Just. How should I put it? Like it can perform something very energy demanding as well. So, if it's some really laborious, strenuous process then that would be very helpful. The weaknesses are that as I said a minute ago, for short term if you're doing one day say and you expect great results in that day the chances of you failing over are very high. I have the feeling; I mean you need to do a lot of these to get it. But it would repay the amount of time that you invest in, if you actually are investing in something that's going to run for a longer period of time.

A: [00:01:31] mmm yeah maybe be it pay like that. I mean all time.

CS2-009 (Vel): [00:01:33] Or well if you're not like a super pro.

A: [00:01:37] Yeah, you need to master it. I mean to get comfortable enough. But I think I will say that about for almost any tool. But you're absolutely right. CS2-012 (Ele) anything else?

CS2-012 (Ele): [00:01:47] I find that you need to master it and it takes time to be comfortable and it's not so much about what's the problem of the robot is about the problem of the gap between the user and the robot. I feel like it's interesting but then it takes such a learning curve. Is not like all right, we can learn it like grasshopper that we can try to learn and play like that. But then you know the upside is the potential of being like what you can do.

A: [00:02:16] What was the most challenging thing about the robot?

CS2-012 (Ele): [00:02:26] The script, understanding the scripting behind like if you asked me to do the script, I would have many issues right now. But then, the process was straight forward, I think.

A: [00:02:35] Okay.

CS2-009 (Vel): [00:02:35] Yeah.

A: [00:02:36] I mean the script can always be fixed by someone. It can also be looking a little more friendly.

CS2-012 (Ele): [00:04:22] Yeah.

A: [00:04:22] Cool. Is there anything that, now that you finish this task... Did you learn anything that might have changed how you approach it at the beginning? From the like... If we redo it like this. Would you change anything?

CS2-012 (Ele): [00:04:31] Is an interesting one, because like. I feel like for what we did. Would we actually produce the same? Like say: Oh, you know that, change that cut or something like that. I feel like I would go for the most possible curvy cuts to test the boundaries of the robot.

CS2-009 (Vel): [00:04:38] Yeah, definitely do more tests. I mean not rely on one of them because in my case it was just completely different. Also, probably not rely Maya for simulation. As in I would do like a lot of tests.

CS2-012 (Ele): [00:04:47] Simulation test?

CS2-009 (Vel): [00:04:47] No, as in physical like what we did in DPM like stretch actual fabric, because I don't know. I have the feeling. Yeah…. Maybe do. You know other tools.

A: [00:04:55] Do you think that the robots can be a tool during the design process? That can be helpful for design?

CS2-012 (Ele): [00:05:00] Yes, but I'm not sure now... Like I feel it's a fun tool to use and I quite like it. But like it has a stage when you are able to use and I'm saying it because like I started using points as grasshopper right now. So, like too much like import everything. Yes. I mean I guess yes. But then it takes experience.

A: [00:05:07] So, you so you would think that right now is more like an obstacle if you had to use the robot for your design process? or You think it could be an obstacle more than an advantage.

CS2-009 (Vel): [00:05:12] Do we consider a situation where we have a saviour. We have a person that has mastered it and provides with the scripts and everything or do we start?

A: [00:05:18] Yeah, I mean like do you think that I mean if you were to like be using it let's say for making models, for testing stuff during your design process? Of course, not like you have to. If I say: you know what DPM, let's say, the design has to be done with the robot. And I'm going to help you, of course. I mean do you think it could be a tool to develop a design or you think it could be an obstacle because it has too many limitations?

CS2-009 (Vel): [00:05:38] No

CS2-012 (Ele): [00:05:38] No, I think is good because. Because we got our hands, we can't... We don't have limitations in the way we've learned to model traditionally. So, you know playing with something that does call for safety and limitations on the way, it's useful because if pushes the way you think. I Would say I would like to use it for my design.

A: [00:05:48] Ok.

CS2-009 (Vel): [00:05:50] Or for design, yeah. I Would definitely like to use it but it really depends on the time span of the project I would say. If it was a longer spanning project, then yeah, because you can do anything. I mean you can do so many more different things than you can do with your hands or with other tools. But that means developing your own tool, like end effector, or running a lot of tests. So, if you have a lot of time, then it's perfect, because you can do so many things. But if you don't have a lot of time, I think it's not perfect because you can do so many things.

CS2-012 (Ele): [00:06:29] Can I just add something. If you ask me now, like: You've got the robot you can use it for your third-year project you're submitting in six months. Are you going to use it and don't touch anything else? No, right now. Because I don't feel I can make much out of it. Whereas you can't just always have someone showing you how to do that one thing, you need to figure it out. Then, it's again.

A: [00:06:50] So, you think that right now it would be a limitation?

CS2-012 (Ele): [00:06:52] Yes.

A: [00:06:53] Okay.

CS2-009 (Vel): [00:06:54] For me it depends though. I mean if I have a really clear idea of what I'm doing with it and it's not anything too crazy. Maybe, I'll be tempted. Because if I have something that only the robot can do.

CS2-012 (Ele): [00:07:14] Yeah then, but if it was like your design project as it was now. You have your building ready. No way. You know what I mean like if you because we haven't. been exactly thought architecture in this way. And I'm not saying that's right or wrong. I'm just saying. You know they are bringing robotics in, like a new theme. So, you know when you have a span of six months and you don't know how to use it it's a challenge, but it's also it can really go wrong.

A: [00:07:42] Then you can test. I mean what about for testing things?

CS2-012 (Ele): [00:07:45] Oh yeah, yeah.

A: [00:07:45] Was there anything on this specific task that you weren't thinking that you could do and you think that the robot was a limitation?

CS2-009 (Vel): [00:08:11] No.

CS2-012 (Ele): [00:08:11] I actually feel on the opposite, I think we were able to do a lot of things.

A: [00:08:14] So maybe its task dependent also.

CS2-009 (Vel): [00:08:18] Yeah like with the pushing. That couldn't have been done, I think otherwise because you use like force. And the cutting. I can't imagine cutting concrete fabric by hand because it will end in disaster. It needs that accuracy.

A: [00:08:38] Do you do physical during your design process? Like just working models, test models all the time or do you only do one model at the end? Like a model of the project?

CS2-012 (Ele): [00:08:50] I do a lot of them.

A: [00:08:51] Yes. Yes?

CS2-009 (Vel): [00:08:53] Well at the end usually and or if my tutors told me to do one. The reason why is just I think I haven't gotten into that comfort of doing models. In the same way as I feel the robot might be a limitation if I have a very short time to come up with a design the same way. Well I can't say for this year but last year I felt, ok, I have a week to figure out my master plan like what's the quickest way to sketch it out and that's why I kind of never ended up doing models and the same as with the robot. If I have a week to get it done, I'll go crazy like how would I set it up and everything.

A: [00:09:35] Do you think that the information that the robot was giving you on the Kinect, that the feedback, was that helping you? Was that helpful?

CS2-012 (Ele): [00:09:44] Yes.

CS2-009 (Vel): [00:09:45] Yeah.

CS2-012 (Ele): [00:09:45] Because I mean, it can give you precise data that you can't judge by eye

A: [00:09:50] Okay. Did it make you change something? Yeah. Of the way you thought that things were happening.

CS2-009 (Vel): [00:09:56] Yeah.

CS2-012 (Ele): [00:09:57] For sure.

A: [00:09:59] Is there anything about interacting with the robot that you might have thought about? Like any thoughts about interacting with the robot.

CS2-012 (Ele): [00:10:08] It's fun. ...It Was nice If. You. Go. I was going just to say it's so weird. Because we always pass through the room and it's there, and when you see it moving. It's like yes, like Yes!

A: [00:10:21] Okay.

CS2-009 (Vel): [00:10:22] We say I had this. I had master it and had enough experience with it to actually have the comfort and say OK I can actually use it, I think that's the, like, that's the gap. Because it’s so tempting, I can imagine myself seating and doing stuff with it all day. That would be so much fun.

A: [00:10:44] Do you think he is reliable? I mean that what he had to do like scanning, pushing, cutting in these was that reliable?

CS2-009 (Vel): [00:10:51] Apart from the blade accident. But that's more the tool. But the robot, yeah. Seems very reliable.

CS2-012 (Ele): [00:10:59] I, like. He is relatively reliable, but you know. There needs to be like someone guiding through like: Nothing breaks, nothing like offsets. Like it's relatively reliable but I wouldn't leave it to itself to do that definitely. Like I want to be there to check it.

CS2-009 (Vel): [00:11:15] Well, I mean of course to be there. I guess yeah. I would say. He's doing his part of the contract well it's just the fact that I've fucked up everything.

A: [00:11:28] Is there anything about his appearance that made you feel uncomfortable or you think that he's not trustable or not reliable?

CS2-009 (Vel): [00:11:34] No, he is adorable. Oh, I love talking about him

A: [00:11:41] Do you trust him. Do you think you can trust him?

CS2-012 (Ele): [00:11:45] Yeah.

CS2-009 (Vel): [00:11:45] Yeah.

A: [00:11:46] Is there anything that encourage you to trust him or just naturally?

CS2-012 (Ele): [00:11:50] The way it moved. Like, it wasn't what it was... It felt like it was a very controlled process.

A: [00:11:55] Yeah.

CS2-009 (Vel): [00:11:55] Yeah. You have all sorts of stop, you know buttons and like all kinds of options: manual control everything's, so it’s kind of really, you see that nothing can go wrong so far though.

CS2-012 (Ele): [00:12:13] I just want to say. The only thing that I feel is weird about the robot, is the cage and then all that's done supposedly to protect you from it. But I felt like that the thing that detaches you from it.

CS2-009 (Vel): [00:12:29] That, I would agree with. By safety controls I meant that you just have a button that you can press and stops it.

A: [00:12:35] Yeah, not the cage.

CS2-009 (Vel): [00:12:37] No not the cage.

A: [00:12:38] Okay perfect.

CS2-012 (Ele): [00:12:39] Do you think it's actually dangerous? It can actually do something to hurt you?

A: [00:12:44] I mean, like for example in the Bartlett they have them with laser cages so you don't see the cage. Like in IAAC, you saw the pictures of the clay. They don't. So, I mean it can. The problem is that if you program something and then you send it. And because what I explained, but maybe you forgot it, on the first time we met. That it has different ways of reaching a point so you might be predicting that he would reach it like that and then he does this and if you are too near and he hits you, I mean he's a heavy machine at the end of the day. So that's the danger that if you program something and you're like: Oh, he will come and do this and then he comes and does this, and you are and you are here. But I mean he would not walk or he would not like I mean he would not do something totally unpredictable. But that's the danger. I mean like he's pushing and if he's cutting for example and you see it on the simulation, on the software that we have. The Alice software, you see how he's going to go like that. When you send the code to the robot the potential is that he might run into an axis limit because maybe. It wasn't with you that I had to introduce a constraint, was it? Ah, yeah with you. That it had too much rotations. So, I think maybe was the previous team. That when we were sending the pushing it had too many rotations. I had to put a constraint in the code, that if the rotation was more than 360 it had to, more than three fifty-seven it had to deduct 360 for me because it was sending six hundred and forty or something. So, you saw that line of code. So basically, I mean those are the problems that you might run but you would not run into a problem that he will be cutting and suddenly doing like phew that's not a problem. So, you know what I mean, that the problem would be more localized. You might run into these. I mean, because of that we have the simulations and you don't have this image like you see in Alice, you see how it goes. I'm going to show you one. Did you see Alice also?

CS2-012 (Ele): [00:14:45] Yeah.

CS2-009 (Vel): [00:14:46] Yeah.

A: [00:14:47] If it doesn't do the analysis then you might expect him to do this, and then he might do something else, and he might potentially crash the table. Like for example sometimes when I sent the points from grasshopper, at the beginning, when I was trying to calibrate it, I thought he would come like this, and even on the simulation I could see that he is going like this. I had to fix that. I mean if you don't have that, then you might run it across the table, kind of, like you know.

CS2-009 (Vel): [00:15:09] But in your case you have Alice.

A: [00:15:13] Yeah, as long as you have a simulation software you are okay. He wouldn't do anything. And once you do a process, like once you do the cutting, forget about the blade, because the blades are totally different. But when it follows the path for cutting, it would put him to do that path all day. He would do the exact same path. If we put a pen, for example until the pen runs out, and he would not even know the pen ran out so he will keep doing it. And the precision is millimetric, so at not any given point he will suddenly, like by half of the path be like maybe I do something else. That doesn't happen. I hope that answers your question.

CS2-009 (Vel): [00:15:46] Yeah.

A: [00:15:48] Well, that's the questionnaire. Thank you so much. Thank you. Thanks, so much for your time. Fantastic for doing so many things for this task.

CS2-009 (Vel): [00:15:56] Thank you for giving us the opportunity.

CS2-010(Kat), CS2-011(Mar), CS2-020(Soo), and CS2-022(Pro)

A: [00:00:01] So, did you have fun with the task?

CS2-020 (Soo); CS2-011 (Mar), CS2-010 (Kat), CS2-022 (Pro): [00:00:04] Yeah.

A: [00:00:04] Do you think it was an interesting task?

CS2-020 (Soo); CS2-011 (Mar), CS2-010 (Kat), CS2-022 (Pro): [00:00:06] Yeah.

A: [00:00:09] What do you think are kind of the weaknesses of the robot arm?

CS2-020 (Soo): [00:00:19] The weaknesses, in terms of this exercise, it can only push things downwards. It can't really help anything If it's too far down like it can't push it up. Yeah.

CS2-022 (Pro): [00:00:35] I think you also have to know exactly where the start point is, the problem we had and were having is that it wasn't pushing anything. You may really need to know the positions.

CS2-010 (Kat): [00:00:53] I think it would be helpful if the robot had like some sort of laser thing to show where it's pointing towards. Yeah.

A: [00:01:00] So you can know where he's going to go?

CS2-010 (Kat): [00:01:03] Yeah.

A: [00:01:07] What do you think are the strengths of the robot?

CS2-020 (Soo): [00:01:13] Accuracy.

A: [00:01:13] Or working with the robot, I mean.

CS2-022 (Pro): [00:01:15] Accuracy, Speed. You also have to have a certain amount of surprise to be able to use it. Which made me feel a bit scared all the time because we really didn't get to know that much

CS2-010 (Kat): [00:01:34] But I feel like it gives you more control of your form because sometimes if you're working with parametric forms it can look a bit random but if you have the robot, it gives you more control, you know which point what goes where.

CS2-022 (Pro): [00:01:49] Yeah.

A: [00:01:50] That's very good point, what do you think is the most challenging thing?

CS2-020 (Soo): [00:01:57] For me it's like to know where like picture the axis of each arm part.

A: [00:02:05] How will it move when you put the axes? CS2-011 (Mar), anything?

CS2-011 (Mar): [00:02:11] Yeah, because we didn't get to program it really. I think that's the most difficult part and the most time consuming the same because you have to know the coordinates.

A: [00:02:26] But let's say that someone can do the programming for you.

CS2-011 (Mar): [00:02:29] Then that's easy.

A: [00:02:29] Or it could be streamlined.

CS2-022 (Pro): [00:02:31] That's very easy.

A: [00:02:32]. I know the programming can be intimidating I can see that. Do you think that the robot can help you in the creative process in the design process?

CS2-010 (Kat): [00:02:52] Yeah.

CS2-011 (Mar): [00:02:54] Yeah.

CS2-022 (Pro): [00:02:54] Yeah.

CS2-020 (Soo): [00:02:54] I actually think it won't.

A: [00:02:56] Do you think it will limit you?

CS2-020 (Soo): [00:02:57] Yeah because... like you have to.... When you're brainstorming ideas sometimes come up really randomly like for example if you're drawing a floor plan on AutoCAD it sort of restricts your thinking versus a you sketching it up freehand like it comes out of your mind, but then if you work through the robot you have to go through all these programs and then go to the robot which sort of restricts the way you think. Like when you go through the computer programs it sorts of makes you think in a specific way like 'oh I must get the code done'. It doesn't really make you think creatively.

CS2-022 (Pro): [00:03:32] Yeah, you have to have... sorry say it.

CS2-010 (Kat): [00:03:35] You can go through that process first and then.

CS2-022 (Pro): [00:03:38] Yeah if you have the final thing, then...

CS2-010 (Kat): [00:03:42] Yeah to through the robot path.

CS2-011 (Mar): [00:03:43] I think if you leave the robot for the final advice.

CS2-020 (Soo): [00:03:47] Yeah. It's more like for final design.

A: [00:03:59] Do you think that you can think your design in terms of the robot?

CS2-011 (Mar): [00:04:02] And you can do more like experimental models, let's say.

CS2-010 (Kat): [00:04:08] Yeah.

CS2-011 (Mar): [00:04:08] So it cuts fast. Yeah. So, it you have one code and you want to make slight changes you can cut them off or even compare them.

CS2-020 (Soo): [00:04:17] Yeah, if someone is familiar with the code then yeah, I think it will help

CS2-022 (Pro): [00:04:22] In the process, other than that, I mean for me it would be useful only for the final.

A: [00:04:28] You don't think that he can be a tool throughout the process?

CS2-022 (Pro): [00:04:31] For the process, no... at another time.

A: [00:04:36] Do you normally do physical models throughout your design or only at the end, only a final model?

CS2-010 (Kat): [00:04:41] I do, all the time.

A: [00:04:44] working models?

CS2-010 (Kat): [00:04:47] Yeah.

CS2-011 (Mar): [00:04:47] Last year mostly.

CS2-010 (Kat): [00:04:48] Yeah, me too last year. This year not so much.

CS2-011 (Mar): [00:04:50] Not that much model making.

CS2-022 (Pro): [00:04:53] Sketching and then also models.

A: [00:04:54] Do you think it's better to do them at the end or do you like to work through models and prototypes?

CS2-022 (Pro): [00:04:59] Process and then at the end.

A: [00:05:01] So you think it's important to do them through the process? What about you?

CS2-010 (Kat): [00:05:05] Yeah, I think it helps you understand more the three dimensional, so it's easier it you have something to help you do the models faster so you move on faster and then you have a finalized design at the end

A: [00:05:26] Do you think that the scanning was useful? That the information that the robot was giving you about the model was useful in any way?

CS2-020 (Soo): [00:05:33] Yeah.

CS2-011 (Mar): [00:05:33] Yeah, I think when you have something in mind and you can compare with a physical one that's very helpful, because you can have accuracy.

A: [00:05:45] Do you think that the robot was accurate in doing his tasks?

CS2-010 (Kat): [00:05:53] Yeah.

CS2-011 (Mar): [00:05:53] Yeah.

CS2-022 (Pro): [00:05:53] Yeah.

CS2-020 (Soo): [00:05:53] mmm Yeah.

A: [00:05:53] What do you think in general about the robot? Like I mean, not in terms of working with the robot but is there something about the way it looks, it moves or about the way it is that makes you feel uncomfortable / comfortable /that you don't care about?

CS2-020 (Soo): [00:06:16] I think the problem is more like my brain can't process where the X is. So, I'm a bit scared when I use the robot.

A: [00:06:23] You became quite good at the end, I have to say, you were more like no breaking every two seconds (laughs) anything else? No?

CS2-011 (Mar): [00:06:36] I think you just get used to it.

CS2-022 (Pro): [00:06:37] Yeah, I really feel I got used to it, I mean working manually at the end.

A: [00:06:41] Yeah, you were quite comfortable like I got the idea that you were very comfortable in the manual moving... You seem to be like driving like a video game or you like him to look differently or do you think it's okay how he looks?

CS2-022 (Pro): [00:07:03] I would like it to be pink (laughs).

CS2-010 (Kat): [00:07:08] Its quite big.

CS2-020 (Soo): [00:07:08] Fun.

A: [00:07:12] Will you trust him? I mean do you think that he was trustable like.

CS2-011 (Mar): [00:07:16] Yeah.

A: [00:07:16] Like that he would not do anything and what he would do will be done properly?

CS2-010 (Kat): [00:07:20] Yeah.

A: [00:07:20] So, you can trust the robot? Ok, Is there anything else about the robot? Anything that you thought or feel or concerns you or you or excites you?

CS2-022 (Pro): [00:07:34] I suppose if you know the exact position of the thing that is going to be working on, and then the starting positions that you set the robot to be at, then it will be fine like I said before.

A: [00:07:58] Anyone else? Any extra thoughts?

CS2-011 (Mar): [00:08:11] Maybe if it learns more about the cutting, I would understand it better

A: [00:08:21] Well, I hope you had fun. Thank you so much for spending time doing these things.

CS2-010 (Kat): [00:08:27] It was a great opportunity, I think.

CS2-020 (Soo): [00:08:29] Yeah, It's really interesting.

CS2-011 (Mar): [00:08:30] Because we couldn't. We wouldn't get the chance to use it.

CS2-020 (Soo): [00:08:34] Yeah.

A: [00:08:35] I hope I hope, I mean that it help you to, I mean it help you to kind of maybe have ideas maybe, like now you know how it works maybe you can start to think if you want to build something, to do something, what can you do rather than being like an enigmatic machine.

CS2-013(Nad), CS2-014(Iv), CS2-016(Mic), and CS2-028(An)

A: [00:00:22] So, did you enjoy this task?

CS2-028 (An); CS2-013 (Nad); CS2-016 (Mic); CS2-014 (Iv): [00:00:25] Yeah.

A: [00:00:25] Do you feel it was a learning experience?

CS2-013 (Nad): [00:00:28] Definitely.

CS2-028 (An): [00:00:28] Yeah.

CS2-014 (Iv): [00:00:28] A real chance to get in touch with the robot.

CS2-028 (An): [00:00:36] I mean, we won't be able to use this in anytime, I mean no one would do it. I guess it's more that the school is concerned probably everyone would use it. It's cool. The more things we use the more things is responsible for.

CS2-014 (Iv): [00:01:51] I saw a video from the AA with the robot drawing something...

A: [00:01:52] The orange or the white one?

CS2-014 (Iv): [00:01:52] The robot or the painting?

A: [00:01:52] The robot....

CS2-014 (Iv): [00:02:00] The robot looks orange, I think.

A: [00:02:00] Oh, that was the opening day because they only got the robots at the AA like one month ago or something like that and they had them drawing, but we did a workshop last year. We have a smaller robot is a white one and we were doing drawings.

CS2-028 (An): [00:02:17] But I guess it would be quite good to have bought our own robot and claiming the hand drawing thing.

A: [00:02:30] So what do you think are kind of the strengths of the robot? The strengths and weaknesses?

CS2-016 (Mic): [00:02:33] Precision.

CS2-014 (Iv): [00:02:39] That is super precise.

CS2-013 (Nad): [00:02:39] Precise and fast and strong

CS2-028 (An): [00:02:44] But the weakness is that they don't have any awareness of their surrounding at all. It's a shame.

CS2-014 (Iv): [00:02:53] It is really good when you know exactly what you are going to do and continue to do something precise where you input coordinates and stuff like that, it's really good for that.

CS2-016 (Mic): [00:03:00] But if you want to experiment, it's kind of a bit tricky.

CS2-014 (Iv): [00:03:05] Yeah.

CS2-028 (An): [00:03:07] Also it doesn't come across naturally.

CS2-016 (Mic): [00:03:09] And you can do it manually then.

A: [00:03:09] You prefer to do it manually?

CS2-016 (Mic): [00:03:11] Yes, especially in the early phase. But then if it goes to final phase and you need it to be precise, then yeah, the robot

A: [00:03:18] What about if you maybe were more comfortable with the robot? I mean right now was like super-fast. Was like three classes or two, or one.

CS2-028 (An): [00:03:28] Well, we have to learn it. But I guess well often doing it will be pretty easy to do.

A: [00:03:35] Do you think that, I mean on this little task, it was a very small task. But when you did, now that you see that you see how the robot works - and you didn't do your curves - but would you have changed something about the way you were thinking about the design, or the curves or the task in general?

CS2-014 (Iv): [00:03:56] Well yes of course. At the beginning is not that we didn't have any idea of what we were going to do, but it sounded kind of confusing. It was hard to imagine. Wasn't.... I was trying to imagine, but maybe I was imagining something which wasn't exactly like that, I don't know.

A: [00:04:14] Did you imagine the robot would be like this? The actions of the robot...

CS2-016 (Mic): [00:04:20] Kind of...

CS2-028 (An): [00:04:23] I thought it would be more efficient. I mean well because we are not really up to the control that it needs... It seems harder than at least I thought.

CS2-014 (Iv): [00:04:34] Well, that's a problem with computers, that they do what you tell them to do not what you want to do. Does it make sense?

CS2-016 (Mic): [00:04:43] Yes it does.

CS2-028 (An): [00:04:45] You tell it the wrong things.

A: [00:04:47] Yeah, I know. Do you think that robots can help you in your creative process? Like when you are designing, if you know how to use them, do you think they can help you.

CS2-028 (An); CS2-013 (Nad); CS2-016 (Mic); CS2-014 (Iv): [00:05:02] Yes. If I know how to use them

A: [00:05:03] Or do you think there are more of an....

CS2-016 (Mic): [00:05:05] For now, I don't think that's comfortable to say it is.

CS2-014 (Iv): [00:05:10] But if you are doing something super abstract and you know how to use the robot then you can imagine the stuff, because you can imagine how they are going to be built and fabricated.

CS2-013 (Nad): [00:05:19] Yes.

CS2-016 (Mic): [00:05:19] Yeah.

A: [00:05:19] Or you think it’s more of an obstacle right now? For your creative process

CS2-014 (Iv): [00:05:26] Not an obstacle, not really. Is just that we are not used to it.

CS2-028 (An): [00:05:28] Well, I guess it can do way more things than we can do. Maybe it can move way heavier things, more accurately.

A: [00:05:33] What was the kind of more confusing part? Of the task. Or more challenging or that you found.

CS2-028 (An): [00:05:45] The control.

A: [00:05:45] The control?

CS2-028 (An): [00:05:47] I mean well it won't only go forward but you can also change it in different directions, and everything that is.

CS2-014 (Iv): [00:05:55] I haven't thought of the fact that it doesn't know what a person is in space and you have to think about all these things about distance, where it opens, where it goes.

CS2-013 (Nad): [00:06:00] We have to keep specifying and be worrying about how it is operating and mostly if there is stuff going outside of his zone or in its way or going in his way.

A: [00:06:09] Yeah, it only knows itself.

CS2-013 (Nad): [00:06:09] Which is kind of good, if you don't have constraints and you know the space it is working on.

A: [00:06:38] Do you normally do models during your design or do you do them at the end of the design. Or do you do a final model? Or you have like working models?

CS2-016 (Mic): [00:06:44] We do.

CS2-013 (Nad): [00:06:47] Yeah.

CS2-028 (An): [00:06:48] Yeah.

A: [00:06:48] Do you think that the scanning, or the information that the robot was giving you is helpful? Was Helpful at all for understanding what was going on? or for anything?

CS2-013 (Nad): [00:07:19] I am not sure, because it is super precise, the robot but then the scanning, I am not sure.

A: [00:07:19] It's what?

CS2-014 (Iv): [00:07:21] It made me confused

A: [00:07:21] It wasn't very clear?

CS2-014 (Iv): [00:07:23] Not so much that is not clear, but it wasn't that precise. But maybe it's because of the tools, maybe if it had a laser it will work better to place with long distance.

CS2-028 (An): [00:07:39] Although I think the noise was really what was affecting.

A: [00:07:41] The what?

CS2-028 (An): [00:07:44] I mean the noise from the surroundings, someone really shouting or something. Just how when we use scanned frames, there is also quite a huge margin between where the actual frame is and where you scanned from…

A: [00:07:59] Yeah. That's the Kinect way of working.

CS2-028 (An): [00:08:01] Yeah that's a limitation.

A: [00:08:02] Yes, that is true.

A: [00:08:12] Any other thoughts about the robot, about working with the robot that you might have any idea?

CS2-028 (An): [00:08:20] I guess. I mean well because in my design project I'm doing several prefabrication modules. I guess an arm like this can be very beautiful in there. Like now all preparation are done by hand. But I guess if we do like build a whole module, like a car, it would be way faster and you can do more…

A: [00:08:45] Like for assembly line.

CS2-028 (An): [00:08:46] Yeah. Yeah.

A: [00:08:54] Do you think that the robot was reliable? For cutting and pushing or whatever it got to do?

CS2-016 (Mic): [00:09:01] Yeah.

CS2-013 (Nad): [00:09:01] Yeah.

CS2-014 (Iv): [00:09:02] Well... not the blade

CS2-028 (An): [00:09:05] But that was about the blade, the tool.

CS2-014 (Iv): [00:09:05] It wasn't about the robot itself; it was just about the tool.

CS2-016 (Mic): [00:09:07] The table.

A: [00:09:09] That rotation of the table was a fantastic idea, my God.... So painful. What did you say sorry?

CS2-014 (Iv): [00:09:18] The robot did its job perfectly

S2-028 (An): [00:09:19] It's just the tool we gave it in the real world.

A: [00:09:25] Is there anything about how the robot looks that you will change? Or that kind of affects? Or that you are not sure? Or that you think might make it more approachable?

CS2-014 (Iv): [00:09:31] No he is good.

A: [00:09:31] He is approachable you think?

CS2-016 (Mic): [00:09:31] Oh yes.

CS2-013 (Nad): [00:09:36] Yes, it was really nice

CS2-014 (Iv): [00:09:36] It's quite difficult to know which way it is working

CS2-028 (An): [00:09:38] We should give it an aunty face.

A: [00:09:43] Are there anything that concerns you about working with the robot in general? Or interacting with the robot? Like if you were to do another task or a different task?

CS2-028 (An): [00:09:50] Is it possible to give it like a proximity sensor, so if you stand near it will only stop

A: [00:09:59] You can. I mean right now you know it can fully extend up to there, right? Now, you can on the software you can tell him your limit rather than being your actual physical limit your limit is like I don't know. Like you know when they have them in fairs or in exhibitions and they have them moving around you can constrain it and tell him your limit, I don't know on the X direction is here, on the Y and on the Z. So, he will not go further. So, there are physical limits and you can put digital limits.

CS2-028 (An): [00:10:35] Well you just now when we were cleaning up the place and then I think I absolutely thought I'm in the interior, so if like someone is operating an arm without knowing that someone is behind or something. Would it be a good idea... because you know you might hit someone really wrong without knowing it.

A: [00:10:59] I mean when you're operating the robot in manual mode its only 10 percent of the real speed, so it's slow but it can still, like if it knocks you it will still be kind of painful. Normally people have to be, you have to be aware of the robot...

CS2-014 (Iv): [00:11:11] Would this robot hurt you?

A: [00:11:14] I mean it's like any other machine, if you have a bandsaw on it and someone's there, I mean so you have to be. It's a heavy machine. Like for example if you are going to have people come inside or something like that, we can limit his actions to be sure that.......The thing is if you do that. I mean for example we want to cut it won't cut because it's outside of his limits. I hope you enjoyed working with the robot. Thank you very much. Thank you for coming here for so long. Honestly. And thanks for all the help on cleaning and so on.

CS2-013 (Nad): [00:11:59] Thank you for offering.

CS2-014 (Iv): [00:11:59] Yeah, it's a great opportunity.

CS2-017(Jan) and CS2-027(Alex)

A: [00:00:36] So, what did you think.... What Do you think about working with the robot in general: What do you think are the strengths of working with a robot, and what do you think are the weaknesses of working with a robot?

CS2-017(Jan): [00:00:47] Well it was, it was pretty new for us I guess and then a different thing that we haven't done before, and it was a bit fun definitely. But the strengths I think, it definitely can do stuff that people can't do and.... Like in a short time maybe.... I was trying to cut the material and it was just not working. So, it's more precise, I guess.

A: [00:01:17] Anything else?

CS2-027 (Alex): [00:01:18] Yeah, I think the same thing that its Interesting. And I think the engineering part is architecture and coding rather than working with it. Yeah, I think it's very interesting and it's fun.

A: [00:01:29] What do you think was the most difficult thing to overcome of working with the robot?

CS2-017(Jan): [00:01:32] Working with the what?... the robot

A: [00:01:39] I mean of the robot of these problems, was there something that was really problematic for you about the robot?

CS2-017(Jan): [00:01:47] No. Not really.

CS2-027 (Alex): [00:01:48] No.

A: [00:01:49] Is there anything, I mean now that you kind of did the whole exercise, and I know it was a bit rushed, Is there anything that you could do... would have changed of how you initially thought about doing ......about Doing the design exercise?

CS2-017(Jan): [00:02:01] Yeah, probably. I mean, I guess if you keep it simpler, it gets a better shape at the end, I guess...

CS2-017(Jan): [00:02:25] It probably might have been useful to just test the material before doing the design. Just to know how it... how it behaves and what kind of shape is looking better at the end probably.

CS2-027 (Alex): [00:02:52] Yeah definitely the same thing.

A: [00:02:55] Is there anything that you would have done exactly the same way?

CS2-017(Jan): [00:02:59] Yeah, everything (laughs).

A: [00:03:02] Do you think that the robot can help you during the creative process?

CS2-017(Jan): [00:03:07] During the creative process?

A: [00:03:07] Or you think that is more like a limitation during your design process?

CS2-017(Jan): [00:03:13] As I said if I if I know what forms works.

A: [00:03:19] But when you are designing the form, before you know so that's the design process. You think it can help you throughout the design? To test shapes maybe or to know what shape work what shape does not work.

CS2-027 (Alex) & CS2-017(Jan): [00:03:30] Yeah definitely.

A: [00:03:30] Or do you think that is more like a limitation during the design process and it’s more like a tool to use at the end of the design process?

CS2-017(Jan): [00:03:36] No, I don't think so.

CS2-027 (Alex): [00:03:36] Yeah, you can use it throughout the design.

CS2-017(Jan): [00:03:40] It can inform your design process.

A: [00:03:42] Was there anything super confusing? What was the most confusing bit?

CS2-017(Jan): [00:03:46] Well, the Maya thing but yeah no, not really

CS2-017(Jan): [00:04:02] I think a great deal of stuff could be done doing that thing.

CS2-027 (Alex): [00:04:05] I think it was pretty clear.

CS2-017(Jan): [00:04:10] There is a lot of room for experimentation.

A: [00:04:14] You normally do models during your design process or you do them at the end? on your normal design studios.

CS2-017(Jan): [00:04:20] Well when it comes to dpm (laughs) no. But when we have design studio normally, it depends on what your concept is, on what you want to achieve, I guess....

CS2-027 (Alex): [00:04:33] It's a bit confusing then, to do a model to see how it works on shape for instance.

A: [00:04:36] So you don't do them normally, you do final models....

CS2-027 (Alex): [00:04:42] Yeah, it depends sometime we do a study model...

A: [00:04:46] You think that the robot, that the scanning and the information that the robot was giving you was useful?

CS2-027 (Alex): [00:04:52] Yeah.

CS2-017(Jan): [00:04:52] Yeah, in CS2-027 (Alex)'s case.

A: [00:04:58] Do you think it help you kind of understand better the material or inform your design? or what did it help you for?

CS2-027 (Alex): [00:05:04] I think it was more about how it would change like the shape. To see how flexible, it is and the design of the shape.

A: [00:05:23] Do you think that the robot was reliable?

CS2-027 (Alex): [00:05:24] Yeah.

CS2-017(Jan): [00:05:28] Yeah, yeah.

A: [00:05:28] Is there anything.... Do you think that the robot pushing and scanning was reliable.?

CS2-027 (Alex) & CS2-017(Jan): [00:05:37] Yeah.

A: [00:05:37] Is there anything that concern you about the robot: how it looks, how it moves anything at all?

CS2-017(Jan): [00:05:41] No I like him a lot a lot. I love it.

CS2-027 (Alex): [00:05:46] Same.

A: [00:05:47] Do you trust it? If you want to do something with the robot, it will do it?

CS2-027 (Alex) & CS2-017(Jan): [00:05:52] Yeah.

A: [00:05:52] Do you think that it is trustable?

CS2-017(Jan): [00:05:55] Yeah, he is trustable

CS2-027 (Alex): [00:05:55] Yes.

A: [00:05:56] Yeah. Okay. Perfect. I mean that's about it from me. Now, I give you the questionnaire that Janet answered is just a quick like multiple choice thing. Thank you so much guys. Thank so much for your time.

CS2-017(Jan): [00:06:07] We want to thank you to for giving us the opportunity to know what this thing does, is it’s not the scary room with the scary thing anymore.

A: [00:06:14] That's cool. I mean honestly maybe if you think about more ideas maybe in the future about your design and you want to test something just pop by.

CS2-019(Anas)

CS2-019 (Anas): [00:00:00] But. I'd... I really like to try new things and I was like I will give a second chance on this because maybe we go fine, so when the other students told me that you run this project and they said they explore new forms and using the robotic arm, because I have never used it before. I was quite like excited, and I was like yes, I would do it.

A: [00:00:28] I'm very happy you did it.

CS2-019 (Anas): [00:00:29] I thought it was... at the beginning.... I was like Oh... there would be only people from the parametric design. But when I asked and no you'd be free to go and you will try it. So, I was a little bit concerned. I wanted to do it but there was something was pushing me back. But then I was sent here like.... maybe without the skill because I'm not in the parametric, but it's ok.

A: [00:00:55] But I'm glad you did it. I'm very happy. Thank you so much.

CS2-019 (Anas): [00:00:57] Thank you. It was a massive opportunity to learn about a lot of things and that I work with Maya, because last year I was working with 3DSmax, I have never worked with Maya. So, it's nice to try new things and if you see that the program suits you, maybe you can try to learn some more. So, it was a nice experience and I think that maybe in the future I will give it a go with Maya as well. I was also really excited, because I had done the form with the curves, because I’m not really good at curves.

A: [00:02:24] No... it looks quite nice.

CS2-019 (Anas): [00:02:24] But yeah, at the end I was like yeah, I can take it.

A: [00:02:24] Good, I am happy CS2-019 (Anas), Thank you so much. So, let's go, so: What do you think are the strengths and the weaknesses of the robot arm?

CS2-019 (Anas): [00:02:49] Strength of the robot arm are you can build new forms of architecture and you can create things that you would not be able to build manually so you have to do it with the help of the robot. So, I think that by testing new things in the theme of the construction and structure it could be really helpful. Weaknesses is like is not a human, it can't think some things like you have to feed it all the time in order to produce things. It doesn't have the mind to think maybe I'm doing something wrong but humans have to give these directions all the time

A: [00:03:30] Yeah. Absolutely. Is there anything that was like that you thought that was specifically or particularly difficult to do with the robot arm? Like challenging about him.

CS2-019 (Anas): [00:03:46] I couldn't believe that it could be so accurate to cut things like so precisely. I wasn't expecting it will do the curves and all this stuff so precisely.

A: [00:04:01] Oh so you didn't expect him to be precise. You think that you learnt something now? I mean if you were to do the curves again and everything again, would you change something after you finished it now?

CS2-019 (Anas): [00:04:15] I would have changed the way I have approached the curves. I think that now that I see the other students' models, I think that maybe I would have tried more forms but the lack of the time this year you know that we were...., But if I had the time I would definitely do more than one model.

A: [00:04:43] Do you think that the robot arm can help you on your design process? When you are designing something would it be a helpful tool?

CS2-019 (Anas): [00:04:51] I think it can be, and particularly this. Because I love concrete and I have never seen, I could never imagine that a robotic arm can do this with concrete and concrete structures because concrete is a material that is very difficult to use, and that I really like. Because I am a concrete lover. I'm sorry I'm just thinking like new forms with concrete now.

A: [00:05:21] But that is good, that it opens your creative process for more forms of concrete, yeah is quite amazing how it can be shaped. Do you think that the robot arm can be an obstacle for the design process in the way?

CS2-019 (Anas): [00:05:34] Of. Course. I think that it is important that because every time we pass and we just have a sneak view of the robotic arm what he is doing. Like what is going on there. I think we should use it more in our projects. like you can have the opportunity. Because people, specially at the parametric group, they can use it for a lot of the models and also like us that we are not in the parametric group. I think that it doesn't really care the robotic arm. I think we can do many things. It can be really cool. Because we can create models that we can't do it by hand.

A: [00:06:10] Yeah. Is there anything that you were hoping to do but do you think that the robot was a limitation to do with this task?

CS2-019 (Anas): [00:06:27] I don't think.

A: [00:06:27] OK. Do you normally do models throughout your design process? or only at the end?

CS2-019 (Anas): [00:06:31] No, I'm doing throughout the design process. I am doing models all the time.

A: [00:06:38] Do you think that the scanning information that the robot was giving you was that helpful for you?

CS2-019 (Anas): [00:06:42] Yes it was helpful. Specially in my project it was precisely not completely far away from my design.

A: [00:06:53] I mean like right now when we were doing the scanning and the robot was giving you information about how the material deformed, was that helpful for you?

CS2-019 (Anas): [00:07:01] Yeah. I think it was helpful

A: [00:07:02] Was it very different from what you expected. what you were looking with your eyes or you think it was the same?

CS2-019 (Anas): [00:07:08] No, it was quite the same. Wasn't too far.

A: [00:07:10] Oh cool. That's very interesting, nice. So, you think that if the robot can give you information, that information can be useful?

CS2-019 (Anas): [00:07:18] I think that it can see things that with the eye I can't see. And I think that the mind is tricky sometimes, so you need something like to be controlled in order to see things.

A: [00:07:38] Any thoughts like .... about working with the robotic arm, anything that maybe concerns you or that you were worried about or any thoughts?

CS2-019 (Anas): [00:07:46] At the beginning I wasn't...., When you told us to do it manually, I like was oh my god can we actually manage it or is it impossible to do it. But then we had the first time and the first connection, and now if I had to do something manually it was something like powerful, I couldnt believe that I could really tell it what to do.

A: [00:08:18] Do you think that the robot was reliable when he was cutting, pushing. You Think that he would do what he needs to do?

CS2-019 (Anas): [00:08:25] Yeah, but maybe because of the impact of the blade, but that was the tool not the robot. But for my model I didn't have any problems, it was doing what it was meant to do.

A: [00:08:41] So you think in general I mean if he has the appropriate tool, he will be reliable?

CS2-019 (Anas): [00:08:46] Yes.

A: [00:08:52] Is there anything that that makes you trust in the robot or anything that makes you think that he's not trustable?

CS2-019 (Anas): [00:08:58] No, I don't think that is not trustable. Because, I think that they might function in that way in order to save you from mistakes, and to do things that you can't believe or you can't think, so it can overthink without a mind.

A: [00:09:15] Thank you.

CS2-019 (Anas): [00:09:18] Thank you so much.

CS2-023(Har), CS2-024(Ah), and CS2-025(Efst)

CS2-024 (Ah): [00:00:05] It really helped learning how to use the robot.

CS2-023 (Har): [00:00:05] Because it is like the only option you get to look at the robot an actually use it.

CS2-025 (Efst): [00:00:12] I wanted to see how it is in practice like the difference between the cloth and the actual.

A: [00:00:17] What do you think is the strength of working with the robot rather than without?

CS2-024 (Ah): [00:00:32] We get to see like you just said like sometimes maybe the calculations in the computer could be inaccurate on the prediction, when predicting how the cloth would react, and it allow us to see how it reacts in the real world so we can then react to it afterwards.

CS2-025 (Efst): [00:00:51] It is faster than the hand.

CS2-023 (Har): [00:00:54] Yeah. I guess you just keep like.... It's easy to do like lots and lots of things and do a more rigorous experiment rather than you doing it by hand, obviously every hand is a bit different, so you can test a lot of things and is quite quickly

CS2-024 (Ah): [00:01:07] Mass producing.

A: [00:01:20] Do you think that it can help a creative process like when you are designing? Is there anything that now that you saw how the robot works; is there anything that maybe you think like you could add or that gives you some thought?

CS2-023 (Har): [00:01:46] I feel I need to know completely how it works because otherwise I would feel very restricted.

A: [00:01:47] So you feel It's more like limitations right now that the robot does.

CS2-023 (Har): [00:01:49] Yeah, because I don't know how to use it so well. Once I Once you understand how to use it well, then it opens up a lot more things; to be able to just take your model from the computer to actually fabricate it, yeah it could be useful.

CS2-024 (Ah): [00:02:07] Using it as a free hand tool would be quite interesting. Without pre-programming anything. I know that that's less sophisticated but if I want paint something or to draw something and yeah, I think that in that area it's quite interesting because what you could do and could be possible.

CS2-025 (Efst): [00:02:38] I also see the limitations between your design and real world. So, you see that I might have left a gap which maybe was okay in the design but in the actual world is maybe small.

A: [00:02:52] Well I think you replied to these. Like some things seem more like confusing or limiting than necessary. Do you do physical models during your design process?

CS2-024 (Ah): [00:03:02] Yeah, we do.

A: [00:03:02] A lot? During the design or at the end? Or just for the final project?

CS2-024 (Ah): [00:03:05] during.

CS2-023 (Har); CS2-025 (Efst): [00:03:06] During and at the end.

A: [00:03:09] Do you think that the feedback -like the scanning- gave you some information, that I mean that kind of process can in the future give you information on your design if you keep using that.

CS2-024 (Ah): [00:03:18] Oh. Yeah, I think you can see a more accurate sort of method to how your design is being developed. If you're modelling and scanning it and going back to it you can see that development.

CS2-023 (Har): [00:03:32] It's a more scientific way.

CS2-025 (Efst): [00:03:35] It's an informative process basically, I think, you can double check and go back and see how are the things going.

A: [00:03:43] So if the robot was going to only be giving you information right, like a feedback tool that would be a helpful function for a robot. Do you think?

CS2-024 (Ah): [00:03:49] Yeah.

A: [00:03:50] Good. Is there anything that you kind of thought about working with the robot initially?

CS2-023 (Har): [00:03:56] Before doing this?

A: [00:03:58] When you started to use it and to try it during the first the first day that we tested it.

CS2-024 (Ah): [00:04:05] I didn't think it'd be as interactive as it was. I didn't think we would actually be in the cage like playing with the robot, testing it. Just having fun with it. I thought it was going to be stricter maybe. It was nice that we got to have fun with the robot.

A: [00:04:22] That's good. Is good that you enjoyed it. That was the idea, that you also have fun. Is there anything that concerns you about the robot? Like the way it looks? Do you think it should be different? Is there anything that might make you like influence your trust or how you feel about him?

CS2-024 (Ah): [00:04:44] No not really.

CS2-025 (Efst): [00:04:44] If it had some sensors maybe.

CS2-024 (Ah): [00:04:45] Or maybe a pressure sensor.

CS2-025 (Efst): [00:04:47] Yeah. Yeah.

A: [00:04:50] What would make you trust him more; if he had a sensor?

CS2-025 (Efst): [00:04:52] Yes.

A: [00:04:52] Mmm. Okay.

CS2-024 (Ah): [00:04:54] And if this cage is not around it might make me trust it more.

CS2-025 (Efst): [00:05:07] If he was aware of himself, as well as of others it will make him like more reliable. and more trusted.

CS2-024 (Ah): [00:05:17] The robot isn't or is aware of Itself?

A: [00:05:18] He's aware of himself. He knows where he is.

CS2-024 (Ah): [00:05:20] It just doesn't matter like if you're there.

CS2-025 (Efst): [00:05:22] Yeah.

CS2-024 (Ah): [00:05:22] It won’t stop.

A: [00:05:24] He doesn't know anything else. The only thing he knows is where he is.

CS2-025 (Efst): [00:05:28] Yeah, if he knew like where everyone else was as well. Yeah.

CS2-023 (Har): [00:05:31] Yeah. I guess if you could tell it that this is where you're working, and if it comes in, that it's not what you are expecting this, is that not possible at all?

A: [00:05:41] You can restrict like for example right now it's not restricted so that's why it can move right but we could tell him like you know: only move like between one meter to the left to one meter to the right. So that can be done. I mean in this case I think we haven't done that because normally they don't allow people to go in and to play with it. Cool. Thank you. And I only need you to answer some questions is like multiple options like one of these.

INITIAL EXPLORATIONS

CS1-001 (Gio)

A: What are the tools that you normally use to design?

CS1-001 (Gio): Handmade drawings, AutoCAD and SketchUp

A: Is it common for you to make physical models of your projects?

CS1-001 (Gio): Yes, we always have to made physical models

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-001 (Gio): Amazing!

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-001 (Gio): The software was a challenge in the beginning but I really liked all of them and I want to apply it on my academic/ professional life

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-001 (Gio): Yes. Using the robot, I could understand the materials and also the robot arm better.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-001 (Gio): Yes, they are important, specially the movement and limits. I did my design already thinking if the robot or the others machines could do it.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-001 (Gio): I still don't have much access to robots but I would love to work with it and learn more about it in the future.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-001 (Gio): It's definitely something that added to my way of thinking architecture and I hope to use this knowledge on my projects and designs.

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-001 (Gio): No, I didn't have problems with the robot.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-001 (Gio): I didn't have much time to proper use the robot to my design.

A: What name will you give to the robot?

CS1-001 (Gio): Robotie

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-001 (Gio): The laser cut and 3D printer.

CS1-002 (Bea)

A: What are the tools that you normally use to design?

CS1-002 (Bea): Before the course I used to draw ideas manually, and then use AutoCAD and SketchUp to represent it.

A: Is it common for you to make physical models of your projects?

CS1-002 (Bea): Yes

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-002 (Bea): I was really surprised and excited the first time I saw it, I guess a word would be "wow".

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-002 (Bea): Not directly, here in Brazil these techniques are not very explored during the academic life. What got me interested was the fact that my favourite buildings or designs were digitally generated.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-002 (Bea): Yes. This experience made me think much more about the process of creating and materializing the projects.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-002 (Bea): Yes, especially during the rhino cuts experiments, that opened up a whole pack of possibilities that I didn´t know about.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-002 (Bea): First it was a little scary for me, and then it became really exciting and rewarding.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-002 (Bea): I think it opens a range of possibilities, it gives you a way to do some forms that manually you couldn´t or would be much more difficult, and gives more precision. It gives you a kind of freedom to create, even with its limitations.

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-002 (Bea): During this experience no, but I can imagine how that could happen, considering the axes.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-002 (Bea): I think it was already helpful.

A: What name will you give to the robot?

CS1-002 (Bea): I actually named him Baymax during the workshop, referring to the Disney movie Big Hero6. In the movie, Baymax is a robot that cares for your health and state of mind. Considering that this experience for me meant recovering my passion and my wish of doing architecture and design for life, I thought it was appropriate.

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-002 (Bea): I can imagine myself using all of them, and I´d like to. Each one has its limitations and its possibilities, and I think combining them all or at least knowing then it is my wish considering the opportunity of getting in touch with it.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-002 (Bea): No, I think this experience provided the right amount of knowledge considering the fact that a lot of us didn't have any experience in the area or with the tools. It gave the same opportunity for those who had and for those who never heard of it before. It was enriching and challenging, made me wish to know more, and now, to search for it, and improve myself.

CS1-003 (Cas)

A: What are the tools that you normally use to design?

CS1-003 (Cas): Computational tools like Auto CAD, 3ds Max, Revit, Maya, Rhino and basic Grasshopper skills, and sketches and 3D models.

A: Is it common for you to make physical models of your projects?

CS1-003 (Cas): Usually it is not that common for me, just when I have to present the model for a client. Now, that I understand more the concept of experimentation, it has become a usual thing, building models, using the 3D printer, testing new designs.

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-003 (Cas): My reaction was, at the beginning, was not to break or damage the robot, so maybe some meters away from it. Something between awesome and challenge.

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-003 (Cas): These days, studding some designs from Zaha or BIG, I used to get interested in how to draw those executives projects, so that was the challenge that brought me to this workshop. Maybe, just at the last day, after the presentation I realized that this is not about how the building ends, but much more of how to achieve the form and concept, so how it begins.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-003 (Cas): The relation between an architect and his project it's not only in the paper or screen, when design not only have to consider sizes and shapes, have to concern as one big structure that has to stand by its own. A basic way of connecting those two points, the idealistic and the real, is by adding the material. The Robot and computational software are only tools that can be used to explore, it is how you apply these instruments that change the way of thinking, and that's the relationship with the material that has shifted. The way of exploring the possibilities to a higher level, different shapes and forms that leads to new construction methods, the metaphor of the man and the machine. By using a new instrument, the Robot and Grasshopper, combined creating never before realized buildings, not only just to show knowledge but to add new experiences for those that will use this space.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-003 (Cas): The robots' limitation is something that you have to consider during your design, arm's length, the weight of the object or the material, the size of your block, all this have to be insert in, like an algorithm to be follow. That is something I realised, either you change your design or the robot will, so it must be adapted, and that should not be consider as an limitation, that's your chosen tool and it's not your design that should adapt to the robot, it's the way of thinking. In the screen the project can flow freely without any constrains, when the forces are added and it has the correct material and building process the role idea might be affect considering all factors before is the correct way.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-003 (Cas): Getting so close to a Robot and been able to interact with one are all new experiences for me, I graduated almost 10 years from now and we didn't have this methodology or even the idea of using robots into our projects. Off course, catenaries, geodesics and curves, especially Niemeyer's, I saw a lot, but with different eyes. You have so much familiarity using this processes that made me so interested in absorbing this knowledge, now I thing that the best way to use all the potential is to experiment.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-003 (Cas): The process of design has to change not only because of the new tools that can be used, but also because of an entire new possibility to be explore.

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-003 (Cas): Sometimes the robot does whatever do you want whereas in others you start feeling that the robot has his own personality.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-003 (Cas): It is tough for me to have an opinion on this subject; it was the first time interacting directly with a robot, I just can say that having a second chance will might help me to interact more with the robot. All my concepts and ideas had a change, how to confront and to begin a design have to pass through a new concept, digital fabrication it is now something that I want to know, those are all tools to reach a form, my way of thinking has changed.

A: What name will you give to the robot?

CS1-003 (Cas): Mr. Bean, soundless, British, in this case, and funny.

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-003 (Cas): The 3D printer is much likely to be used in a regular base at my office, but the robot for me is like an challenge so now one of the things that I want to do is to design considering the usage of this tool, but off course I have to improve my skills before that, with Maya and specially Grasshopper.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-003 (Cas): I don't have a specific suggestions or anything, now I'm more concerned into get deep in those concepts that we fly through, maybe the only thing that I can add is if the workshop could be longer, more days should be necessary, we have one project been cut by the robot, time was an issue. Thanks for everything hopefully we can meet again.

CS1-004 (Mar)

A: What are the tools that you normally use to design?

CS1-004 (Mar): Pencil and paper, AutoCAD and Sketchup

A: Is it common for you to make physical models of your projects?

No

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-004 (Mar): Anxious

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-004 (Mar): Yes, the possibility not just to prototype, but to build the architectural projects using robots and automated systems. The need to reduce steps and intermediates in traditional construction method, to make it more affordable, productive and precise. To free the creation process in architecture. To achieve new shapes and relations to people.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-004 (Mar): A lot, it increased my reach, possibilities and vision. And my enthusiasm.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-004 (Mar): Yes, the apparently simple shape we designed was too difficult to achieve because of those characteristics. Of course, our lack knowledge was a huge limitation too.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-004 (Mar): Although this relationship should get deeper, was a changing moment in my architectural live.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-004 (Mar): Construction is a complex process with a great number of disciplines that should fit perfectly with each other. The robot can bring us precision and capacity to work in complex shapes, that allow great freedom in creation process and choice of materials. Still, give us more control of the construction process that can represent less costs and respect to the schedule.

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-004 (Mar): Yes, I'm still learning his moves, limitations and possibilities. In the workshop I had to drop some ideas to bring back forward.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-004 (Mar): Start earlier the fabrication of our own model. So, we can have more time to learn, improve the design and try again.

A: What name will you give to the robot?

CS1-004 (Mar): Dave

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-004 (Mar): The robot and the router. They allow me to work in large prototypes and even in final products to build. The router is more accessible because of the woodwork partners I already spoke to. But the robot is much more flexible and is the one I'm looking someway to involve immediately in my professional live.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-004 (Mar): Somehow it should be simpler to communicate with the robot from the software and to extract his moves from a pre designed shape. Probably it's just a question of knowledge for me that I need to go deeper, let's see. Thank you all for sharing all this with us, it was amazing!

CS1-005 (Ema)

A: What are the tools that you normally use to design?

CS1-005 (Ema): Until now I began my design with drawings (sketches) on paper - were I translated my intentions to the design. After that I used 2d and 3d software to pass for digital way my pre-conceived intentions. Physical models with few details, to help me to understand the transitions between my project intentions in 2d and 3d. More detailed models to present and explain the project to the spectator (professors or clients).

A: Is it common for you to make physical models of your projects?

CS1-005 (Ema): Yes. I always used to make physical models to understand my projects. I always had difficulties in translating my project intentions only in 2d. The physical model was always essential, even with few details.

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-005 (Ema): WOW, that´s cool!

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-005 (Ema): What fascinates me more in digital design and fabrication techniques are the range of possibilities of thinking the project. That makes the creative process more individual and particular, in the architect's point of view. We are human beings, distinct, we can obtain much more interesting results if we use tools or project processes in which we feel more comfortable (or challenged!). The question is to instigate creativity. Answering that I did not told about the advantages that we can obtain taking part of parameters to enhance efficiency, etc.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-005 (Ema): Absolutely. Understanding the way how the robot works I perceive the immense range of work possibilities over a lot of different materials and I felt an urge creative strength internally. The robotic arm allows that we work the material in a lot of different ways that we had never thought before. That makes me comprehend the concept of materiality.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-005 (Ema): The robot characteristics are essential during the design process. Initially I tried to develop very simple forms using Rhino. I perceived that these forms, simple for us, are complex to the robot. At this moment we chose to accept the robot characteristics and do not manipulate so much the design, taking advantage of the robot characteristics, like speed, movement and limits, in a much more natural way. This way, he had a much more complex design – and much more interesting. It means that was much easier to construct a complex object using robotic arms than a simple one.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-005 (Ema): I felt comfortable with the robotic manipulator. I was not afraid. I felt certain difficulty by administrating two coordinates nucleus (robot and tool). Looks easier try to be focused in one nucleus each time. I imagine that by practicing it would be more natural.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-005 (Ema): Now I feel more comfortable to develop and construct more complex forms. I feel we have more available time to deepen in conceptual aspects of design, as we have more freedom to design and the help of robotic arm to build things that would only be possible providing a lot of time of human work (manual).

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-005 (Ema): Absolutely! We always try to dictate the rules (like in life!) but we are not always on control. It means, if we know to be flexible to the constraints, we can achieve more interesting results. The surprises can be very good or bad. If we learn how to work with the adversities, we can obtain more creative and efficient solutions to our problems.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-005 (Ema): Tried to not have so much control over my design to know better the qualities and limitations of the robot. I achieved more interesting designs when decided to reduce the manipulations over the design.

A: What name will you give to the robot?

CS1-005 (Ema): I would call him Robin. He was very sympathetic and very helpful. (Like Batman's assistant).

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-005 (Ema): Among the three used machines (3d printer, laser cutter and robot), I imagine that the one I felt more likely to use in my professional life would be the laser cutter, because the agility, scale and costs. I could to visualize a lot of applications of the robot in architecture but we still need the mediation of the enterprises to have access to these machines in our day-by-day. (Or we can become the entrepreneurs, individually or collectively).

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-005 (Ema): I think the workshop was very nice, very helpful and very exciting. I think that is question of time of “playing” with the robot to enhance our design strategies. Learn better their characteristics and limitations. Thank you so much!

CS1-006 (Hen)

A: What are the tools that you normally use to design?

The software I usually use are AutoCAD, Sketchup and Photoshop. Lately I’ve been switching from AutoCAD to Revit

A: Is it common for you to make physical models of your projects?

CS1-006 (Hen): I used to do in graduation, not anymore

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-006 (Hen): I was quite amused when I saw it, I felt like if I were in some sort of high-tech environment! As for the reaction, at first it arouses curiosity, and afterwards I started imagining the different uses it could have. Probably my first word was a swear-word; but something like "this is insane", or "wow"

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-006 (Hen): I’m not sure I understood this question very well; I recall in my professional life I worked once in a project that had 13 perforated panels measuring 1,2m width X 3m tall. This panels were standing side by side and worked together as a frit, that would develop along the extension of the panels. This sort of caught my attention and we kind of did it in a dumb manual way. Since academic life, I have a lot of interest in feature walls too, and I feel like after the workshop the ideas to work this feature walls have grown quite a lot also. Even after the workshop I can say that I’m still more interested in digital design than fabrication. Maybe because is something more "reachable" in short time distance. Though seeing the foam structure being conceived and produced by the "big dude" was amazing

A: Materiality as defined by Antoine Picon doesn’t refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-006 (Hen): Definitely yes, because it provided us a mean to reach with perfect precision the design intent. We had some limitations (example of the ruled surfaces on the foam) and sometimes it didn’t come as expected, but putting this aside, our possibilities were a lot, and I enjoyed the result very much.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-006 (Hen): I had to change the design, because firstly I came up with some very complicated geometry to cut. I tried to simplify things using only one section path, and later realized it turned out even better because the part we would toss away could also become another piece of usage. So, in the end, it didn't mean that because of the changes our design became poor. Once we adapted our design to fit the robot's conditions, we realized that we had a lot of options to build different things.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-006 (Hen): In the beginning I felt I lacked motor coordination, but within some usages I kind of got the hang of it. As for setting and saving the points for the robot to read, I wouldn't know how to do it myself.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-006 (Hen): As we experienced in the workshop, the robot provided us means to simulate our design and explore different solutions while changing parameters. Of course, considering it was combined to a parametric design, but still, it is very helpful. Also, I appreciated the accuracy and automatic process we could apply in a large scale of fabrication.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-006 (Hen): I struggled a little bit using the robot in the foam, because I think we had little time to use it. Also, I was focusing on different activities in the workshop. I don't really know what would have helped. Maybe a friendlier interface? Although with time I think I understood most of how the manipulation worked, but the beginning was a little confusing.

A: What name will you give to the robot?

CS1-006 (Hen): Cyber Arm!

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-006 (Hen): I think the little dude and big dude are a little bit trickier to use then the laser cut and 3d printing machine. Because you have to you some sort of programming, and the robots are expensive. As for the other two, I think both of them are likely to be used, but I have some ideas using laser cut/cnc for furniture design.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-006 (Hen): Yes; always keep in mind where the compressor will be installed, preferably far… I would say to hold on to the strategy you made, of showing us first how the robot worked and afterwards giving us time to design the "product". It worked!

CS1-007 (Jut)

A: What are the tools that you normally use to design?

CS1-007 (Jut): Adobe Package, Rhinoceros, Grasshopper.

A: Is it common for you to make physical models of your projects?

CS1-007 (Jut): Yes. It helps me to see what can be improved and how the product it's going to look like.

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-007 (Jut): I think I was mesmerized, both for the robots and the idea of using it in design.

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-007 (Jut): It wasn't exactly challenges, but as I discovered the digital fabrication and how it could make my way of designing easier, my way of thinking changed and I started to research and dig up everything I could to find out more about these techniques.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-007 (Jut): Yes, even though with the machines you don't actually get to feel the materials in your hands, like the flexibility, toughness and texture, you need the sensibility to learn what the robot arm can understand and its strength.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-007 (Jut): You need to understand how the robot works, such as its movement, speed and limits before start using it. I didn't need to change the design itself, but the way it was going to be build, like number of pieces, formats, sizes, angles. I believe the harder part, after designing it, is program the movements of the robot.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-007 (Jut): I have a good relationship with the robots. I think I understand how it can be useful to me and how I can take the best out of its functionalities.

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-007 (Jut): For now, I see an industrial robotic manipulator being useful only in an academic way, like finding out new materials, technologies and building techniques.

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-007 (Jut): Yes, because the robot doesn't know about anything besides itself. So, we need to negotiate its movements and how it is going to read the code, like which path it'll make from a point to the other one.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-007 (Jut): Learning more about the programming process and coding would have helped the integration. Speaking the robot's language would have made the process easier and more natural.

A: What name will you give to the robot?

CS1-007 (Jut): Little blue dude

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-007 (Jut): Probably the robotic arm, because it's more versatile, you can change the tool and work in many different ways. Also, it is a very precise technique.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-007 (Jut): It's a new way of doing design so everything is very different for most of the designers and architects. I believe we need to continue encouraging its use, because this is definitely the future of designing.

CS1-008 (Juc)

A: What are the tools that you normally use to design?

CS1-008 (Juc): Rhino and Grasshopper. And now Maya (thank you!)

A: Is it common for you to make physical models of your projects?

CS1-008 (Juc): Yes, I use 3d printer often for prototyping.

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-008 (Juc): I was amazed. I had contact with robotic arm before at another workshop, but in the end, it didn't work properly, what was frustrating. So, I had high expectations to use it at this time.

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-008 (Juc): Yes, my recent research to fabricate connectors to construct complex structures.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-008 (Juc): I think robots and other machines can add more control, precision and power to this relationship. And it changes it once the material manipulation doesn't depend of hands' abilities anymore, but our capability of think the design and programming the machines properly.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-008 (Juc): Yes, we had to consider the axes' movements and also the limit distance that the robot could reach, the quantity of points and the distance between them influenced the speed and uniformity of the cut. We had to flip the coordinate planes direction so the robot could reach all the points.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-008 (Juc): I was focused in to learn how the robot works, I think it was the first steps and I hope to have the chance to play with it again soon. It was great!

A: What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

CS1-008 (Juc): Considering the short experience I have in construction I can say it's a big challenge to communicate the design information to the builders and try to fit it to their abilities and techniques in order to come out with a building as close to the design as possible. The more complex the geometry, the more challenging it is. Many times, this gap (between the design and workers techniques) limits the design process. I think robots and other digital fabrication machines can cross these limits, putting architects on control of the construction process at the same time it brings more precision, less mistakes, less material waste and more safety.

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-008 (Juc): I can't imagine myself negotiating with a robot, but when something doesn't work with the robot it means we have to change the design strategies or fix our mistakes. Yes, we had to change our design for the foam cutting to fit to the robot's limits.

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-008 (Juc): Well, I felt a disconnection between our design proposals and how it would be fabricated with the robot. Maybe we could learn first of all how the robot works and how would we use it, with which tools and materials we would work with, and then to start the design process regarding this information.

A: What name will you give to the robot?

CS1-008 (Juc): The small one = Zé Silva; The big one = Terminator

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-008 (Juc): For now, I think 3d printer and laser cut are more accessible for me, I am particularly excited with 3d printer's potential to produce constructive components and how it can optimize structural assembly. But I can imagine in a near future the robots replacing humans in construction, producing components in large scale and assembling it as in automotive industry.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-008 (Juc): I feel there is a huge gap between the way we design and all these technologies' potentials. Mainly in Brazil, I feel we are stuck on 20's, we have hundred years delay in construction technology. But, in general, when we compare construction's industry with automotive, aerospace, or information technology, construction's its far away from the rest, it seems we are in different ages. So, I think we need to run out to reach the maximum potential these technologies can offer us in order to meet high performance in buildings. And I think you are in the front line of these knowledges, bringing it to us and pushing us to create the necessary conditions to achieve it. Thank you, a lot, the workshop was great!

CS1-009 (Raf)

A: Is it common for you to make physical models of your projects?

CS1-009 (Raf): Yes

A: Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

CS1-009 (Raf): Impressive!

A: When you started the workshop, did you have many challenges in your professional /academic life that got you interested in digital design and fabrication techniques?

CS1-009 (Raf): Yes, in a lot of cases there was some difficulties to represent and create some of my ideas in my academic life, and I wondered a lot of how to model and fabricate in the quickest way.

A: Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

CS1-009 (Raf): Yes, it makes me believe that hyperbolic are possible to make and to see a product fabricated and feel it.

A: Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

CS1-009 (Raf): Yes, not ever thing is easy to fabricate, and also time is important, although you can estimate the time of fabrication, but time optimization is one of the crucial aspects.

A: How will you describe your relationship with the industrial robotic manipulator?

CS1-009 (Raf): Not so intuitive, but with time I got the hang of it

A: Were there times when you felt like you needed to negotiate with the robot?

CS1-009 (Raf): Just to deal with the spatiality some times in the simulation you could see that the robot would touch the hotwire, so we had to redesign the product

A: What would have helped you to integrate the robot to your design process during the workshop?

CS1-009 (Raf): Basically, the spinning arm part, I really liked the results!

A: What name will you give to the robot?

CS1-009 (Raf): arMold, The Fabricator! Or Come with me if you want to fabricate.

A: Which machine of the 3 used during the workshop for digital fabrication you feel more likely to use in your professional life? And why?

CS1-009 (Raf): 3D printing, most accessible.

A: Do you have any suggestions or further comments about design strategies when using robots?

CS1-009 (Raf): I wonder if it is possible to mix the 3D printer with a robot arm. So, you would have a 5 axes 3D printer.

APPENDIX J TEAM FLUENCY SCORES FOR EACH ITEM OF THE QUESTIONNAIRE

Participant	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Q.1C	4.0	5.5	5.5	5.5	5.5	5.5	2.5	5.5	5.5	5.5	7.0	5.5	5.5	7.0	7.0	7.0	7.0	5.5	7.0	5.5	5.5	5.5	5.5	5.5	5.5	5.7	0.1
Q.2R	5.5	7.0	5.5	5.5	5.5	7.0	7.0	5.5	5.5	7.0	5.5	5.5	7.0	7.0	5.5	5.5	5.5	5.5	7.0	7.0	2.5	5.5	4.0	4.0	4.0	5.7	1.2
Q.3C	5.5	7.0	5.5	5.5	4.0	5.5	2.5	5.5	5.5	5.5	5.5	5.5	5.5	7.0	7.0	5.5	5.5	5.5	7.0	5.5	7.0	5.5	5.5	5.5	4.0	5.6	1.0
Q.4S	7.0	7.0	5.5	5.5	7.0	5.5	2.5	4.0	5.5	7.0	7.0	7.0	7.0	7.0	5.5	7.0	7.0	5.5	7.0	5.5	7.0	5.5	5.5	7.0	5.5	6.1	1.1
Q.5R	5.5	5.5	7.0	4.0	2.5	5.5	7.0	4.0	5.5	7.0	5.5	5.5	7.0	5.5	5.5	5.5	5.5	5.5	7.0	7.0	5.5	4.0	5.5	2.5	5.5	5.4	1.3
Q.6R	2.5	2.5	2.5	2.5	4.0	2.5	2.5	1.0	4.0	2.5	2.5	2.5	1.0	2.5	4.0	4.0	2.5	2.5	2.5	2.5	1.0	4.0	2.5	2.5	2.5	2.6	0.9
Q.7H	5.5	5.5	4.0	5.5	5.5	5.5	7.0	4.0	5.5	7.0	4.0	4.0	5.5	7.0	4.0	4.0	4.0	5.5	5.5	4.0	5.5	4.0	5.5	5.5	5.5	5.1	1.0
Q.8HR	7.0	7.0	5.5	5.5	5.5	5.5	5.5	2.5	5.5	7.0	5.5	5.5	5.5	5.5	5.5	7.0	5.5	7.0	7.0	7.0	4.0	5.5	5.5	5.5	5.5	5.7	1.0
Q.9U	5.5	5.5	5.5	5.5	7.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	7.0	7.0	5.5	5.5	4.0	5.5	5.5	5.5	4.0	5.5	5.5	5.5	5.5	5.6	0.7
Q.10E	5.5	4.0	2.5	5.5	4.0	4.0	4.0	5.5	4.0	4.0	5.5	4.0	7.0	5.5	7.0	7.0	7.0	7.0	7.0	4.0	4.0	4.0	4.0	4.0	7.0	5.1	1.4
Q.11R	2.5	2.5	2.5	2.5	5.5	5.5	2.5	4.0	4.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4.0	1.0	7.0	1.0	2.5	4.0	2.5	4.0	2.5	3.1	1.3
Q.12C	7.0	7.0	5.5	5.5	5.5	7.0	2.5	5.5	5.5	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	5.5	7.0	5.5	7.0	7.0	4.0	6.3	1.2
Q.13S	5.5	7.0	5.5	5.5	5.5	7.0	4.0	5.5	5.5	7.0	5.5	7.0	7.0	7.0	5.5	7.0	7.0	5.5	7.0	5.5	7.0	4.0	5.5	5.5	5.5	6.0	0.9
Q.14R	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	7.0	5.5	5.5	5.5	5.5	4.0	5.5	4.0	5.5	7.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	0.6
Q.15U	5.5	5.5	4.0	4.0	2.5	7.0	7.0	5.5	4.0	7.0	4.0	4.0	5.5	5.5	5.5	5.5	5.5	5.5	7.0	7.0	4.0	4.0	5.5	5.5	5.5	5.3	1.2
Q.16C	5.5	5.5	7.0	4.0	4.0	5.5	4.0	4.0	5.5	5.5	7.0	5.5	5.5	7.0	5.5	7.0	4.0	5.5	7.0	4.0	4.0	5.5	5.5	5.5	4.0	5.3	1.1
Q.17U	5.5	5.5	2.5	2.5	2.5	4.0	4.0	2.5	2.5	5.5	5.5	5.5	4.0	5.5	4.0	5.5	4.0	2.5	2.5	2.5	5.5	2.5	4.0	2.5	2.5	3.8	1.3
Q.18HR	2.5	7.0	5.5	5.5	4.0	5.5	4.0	4.0	2.5	4.0	4.0	2.5	5.5	4.0	2.5	2.5	5.5	2.5	2.5	5.5	1.0	4.0	4.0	4.0	4.0	4.0	1.4
Q.19EI	5.5	7.0	5.5	5.5	2.5	5.5	4.0	5.5	5.5	5.5	7.0	5.5	5.5	5.5	7.0	7.0	4.0	5.5	7.0	5.5	5.5	5.5	5.5	5.5	5.5	5.6	1.0
Q.20L	2.5	7.0	5.5	7.0	5.5	4.0	2.5	5.5	5.5	7.0	7.0	5.5	7.0	5.5	7.0	7.0	7.0	5.5	2.5	5.5	5.5	5.5	5.5	4.0	5.5	5.5	1.4
Q.21	2.0	6.0	6.0	6.0	5.0	4.0	3.0	5.0	6.0	4.0	6.0	5.0	4.0	2.0	3.0	2.0	1.0	6.0	3.0	3.0	3.0	4.0	5.0	4.0	5.0	4.1	1.6
Q.22	6.0	2.0	5.0	4.0	6.0	2.0	6.0	6.0	6.0	7.0	4.0	4.0	5.0	7.0	4.0	4.0	3.0	6.0	7.0	6.0	3.0	5.0	3.0	5.0	5.0	4.6	1.7
Q.23	5.0	5.0	3.0	3.0	5.0	5.0	7.0	6.0	5.0	5.0	4.0	4.0	7.0	5.0	5.0	6.0	6.0	5.0	4.0	7.0	4.0	6.0	4.0	6.0	2.0	4.8	1.5
Q.24	5.0	5.0	6.0	6.0	4.0	4.0	4.0	6.0	5.0	5.0	7.0	5.0	7.0	7.0	5.0	2.0	4.0	6.0	7.0	6.0	3.0	5.0	5.0	6.0	2.0	4.9	1.6
Q.25	3.0	3.0	6.0	6.0	5.0	5.0	2.0	3.0	3.0	4.0	3.0	4.0	1.0	7.0	3.0	3.0	2.0	4.0	6.0	2.0	3.0	4.0	5.0	3.0	4.0	3.7	1.6
Q.26	4.0	3.0	7.0	5.0	3.0	4.0	2.0	2.0	3.0	5.0	4.0	4.0	2.0	7.0	3.0	2.0	4.0	4.0	6.0	2.0	4.0	5.0	4.0	3.0	6.0	3.8	1.6
Q.27	2.0	7.0	3.0	3.0	5.0	6.0	4.0	4.0	6.0	6.0	3.0	4.0	3.0	7.0	4.0	6.0	4.0	5.0	6.0	4.0	4.0	5.0	4.0	3.0	5.0	4.5	1.4
Q.28	2.0	7.0	3.0	4.0	5.0	5.0	2.0	3.0	5.0	6.0	4.0	3.0	5.0	6.0	4.0	6.0	4.0	6.0	6.0	2.0	2.0	4.0	4.0	2.0	6.0	4.2	1.6
Q.29	7.0	5.0	7.0	6.0	3.0	6.0	6.0	3.0	3.0	3.0	4.0	7.0	6.0	7.0	6.0	7.0	6.0	7.0	7.0	6.0	3.0	3.0	5.0	1.0	3.0	5.0	1.8
Q.30	7.0	6.0	7.0	6.0	4.0	7.0	6.0	5.0	4.0	3.0	5.0	7.0	7.0	7.0	7.0	7.0	5.0	7.0	7.0	6.0	3.0	2.0	4.0	3.0	5.0	5.5	1.6
Q.31	7.0	5.0	7.0	6.0	6.0	4.0	4.0	5.0	5.0	7.0	6.0	5.0	7.0	3.0	5.0	7.0	6.0	5.0	4.0	6.0	4.0	6.0	5.0	5.0	5.0	5.2	1.4
Q.32	2.0	6.0	1.0	4.0	6.0	2.0	5.0	3.0	5.0	1.0	6.0	4.0	4.0	6.0	5.0	3.0	5.0	2.0	4.0	6.0	5.0	4.0	3.0	5.0	5.0	4.0	1.6
Q.33	7.0	5.0	7.0	7.0	5.0	5.0	4.0	5.0	5.0	6.0	6.0	4.0	7.0	5.0	6.0	7.0	6.0	7.0	4.0	6.0	5.0	6.0	5.0	6.0	4.0	5.4	1.4
Q.34	4.0	4.0	7.0	7.0	6.0	6.0	6.0	5.0	5.0	6.0	6.0	6.0	7.0	7.0	5.0	7.0	6.0	6.0	7.0	4.0	5.0	5.0	6.0	6.0	4.0	5.6	1.4
Q.35	6.0	7.0	7.0	7.0	6.0	7.0	6.0	5.0	6.0	7.0	7.0	6.0	7.0	7.0	5.0	7.0	4.0	6.0	7.0	4.0	6.0	5.0	7.0	5.0	6.0	5.9	1.4
Q.36	1.0	1.0	7.0	4.0	7.0	4.0	4.0	7.0	7.0	4.0	1.0	7.0	7.0	7.0	7.0	7.0	7.0	4.0	7.0	4.0	1.0	4.0	4.0	7.0	1.0	4.8	2.4
TOTAL	171.00	193.00	187.00	182.00	174.50	184.50	157.00	163.50	177.00	195.00	184.50	180.00	199.00	213.00	184.00	197.50	178.50	187.00	211.00	175.00	151.50	168.00	172.50	166.50	163.00	180.62	15.09

APPENDIX K RESEARCH NOTEBOOK 1

Notebook 01, the research log (Latour 2005)

This notebook is to keep a detailed account of how we go about doing the research. It should note appointments, discussion with advisers, reactions to research from others, phone calls, internet searches, etc. Anything that describes how we came up with the idea of the research, how we get funding and from where and how we go about finding data. Latour describes it as a "Log of the enquiry itself. This is the only way to document the transformation one undergoes by doing the travel. Appointments, reactions to the study by others, surprises to the strangeness of the field. Without regular documentation on the first notebook the artificial experiment of going into the field, will be quickly lost". He further emphasizes that "even years after, it should remain possible to know how the study was conceived, what sources and persons were met"

"Everything is Data", we need to keep track of all our moves. (Latour 2005, p.133). The task is to deploy actors as networks of mediations (Latour 2005), deployment is not the same as 'mere description'

Latour describes a good ANT account as *"a narrative, description or proposition where **all the actors do something** and not just sit there"* (Latour 2005, p.128). He goes further to say that "*a good text elicits networks of actors when it allows the writer to trace a set of relations defined by so many translations"* (Latour 2005, p.129).

Defining a bad text: that one in which **only a handful** of actors are **designated as the causes** of all others which have no function and serve only as a backdrop. They will keep busy as characters but won't act. Nothing is translated from one to the other since action *"is simply carried through them"*. **If an actor makes no difference it's not an actor**. A bad written account simply transports causalities through mere intermediaries. Translations are watered down into mere displacements. It is not about a few social causes generating a mass of effects.

The text should not only invoke masses of agents but should open the principles of their assembly and render traceable new reassemblages.

Network in ANT is a concept not a thing, an **expression that allows us to check how much energy, movement and specificity our reports are able to capture**. Network is a tool to describe something not that which is described. Networks designate flows of translations; a network is the "trace left behind by some moving agent"

If a description remains in need of an explanation, it means that is a bad description.

Gabriel Tarde *"to exist is to differ"* (Latour 2005, p.137) *"It's the very character of the social to be specific, the name of the game is not reduction but irreduction".* A good account will perform the social in the precise sense that some of the participants in the action will be assembled in such a way that they can be collected together. This is not an easy task neither akin to 'mere description'

Pierre Bourdieu describes how the sociologist task is to purge himself in his descriptions of all perspectives through the extreme application of critical reflexivity*: "The sociologist must beware that: …He has a perspective which does not coincide with others, nor with the overview and over-arching perspective of the quasi-divine observer. The particularity of the social sciences calls upon him to construct a scientific* *truth capable of integrating the observer's vision and the truth of the agent's practical vision into a perspective not known which is put to the test in the illusion of the absolute"* (Latour 2005, p.139).

16.09.16

Meeting with Wassim to review the design experiment and proposal. It originally includes 4 settings – the AA visiting school in Sao Paulo, students from the Welsh School of Architecture, workshop with master students from the DRL at the Architectural Association and the visiting school in India. This will give a range of students from different backgrounds that will evaluate how do they feel about interacting with the robot. Due to the different materials that are going to be used in each case and the different health and safety protocols of each institution, Wassim doesn't want to compromise and prefers for the study to be conducted only with students from the WSA and a questionnaire is applied to the rest. Material and robot implications

20.09.16

Review of the experiment design with Dr Wassim Jabi and Dr Andrew Roberts. A new proposal is tabled to be developed with students from the WSA, the questionnaire and interviews will focus on evaluating aspects of trust and reliance as well as comfort in working with the robot. A design methodology using a simulation software, concrete canvas and a Kinect is proposed and accepted. 15-20 participants are considered enough to validate the experiment according to HCI and HRI literature but the call will try to get as many as possible. Qualitative analysis software atlas.ti is to be used to record and code the process. Dr Roberts suggest using NVIVO which is already available in the university.

Questionnaires have to be changed so they don't go from 'strongly agree to strongly disagree' but use the noun or adjective that is being evaluated as answers to the questions. The participant information sheet has to include the fact that all faces are going to be blurred from any images and videos recorder during the case study.

Methodology and background are accepted but criteria for success has to be defined and a clearer definition of what each parameter is evaluating and its meaning in the overall context of the experiments. This can be referred in the document 'case study methodology and procedures.docx'

The meeting review is satisfactory and the experiment approved.

27.09.16

The revised proposal is discussed with Wassim and accepted. Parameters and criteria of evaluation are clear. It is suggested to increase the number of participants to 60 to get statistical data but this might be done by adding the participants from the other workshops. A conversation with Dr Wouter Pooteringa is suggested to refine the questionnaires and surveys.

The possibility of doing the surveys digitally using an engine like 'survermonkey' is tabled and considered.

30.09.16

Conversation with Dr Wouter Pooteringa regarding the questionnaire. He suggests to make all the open questions in an interview format so that they don't have to be answered in writing. As the number of parameters that is being considered is high the questions are already too many. He agrees with the change from 'strongly agree to strongly disagree' to using the adjective to which the question is referring as evaluation parameter. Comments are made regarding the questions that include double negatives as they can be confusing or guiding the participant towards the answer, this is changed. On the second part of the questionnaire the robot is referred to as 'partner' in a large number of questions. He suggests to change this for simply 'the robot' and add a question of whether participants felt the robot as a partner or not at the end rather than referring to the robot as partner. This is taken into account and changes made accordingly.

14.00

Questionnaire is finalised and ethical approval form submitted and signed by main supervisor – Wassim with the research proposal, research participant information sheet and questionnaires. All of these documents are submitted to start the university ethical approval process with Katrina Lewis.

04.10.16

Call for participant's posters printed and plastered around the school at around 21.00. I also directly contacted Nikolina from SAWSA to post into the SAWSA facebook page as well as year page. Direct contact was also established with Velina from 3rd year asking her for help in passing the voice and posting the announcement in the 3rd year facebook page.

05.10.16

First emails from interested participants started to arrive this morning. An afternoon session was proposed for the 12.10 with the aim of having all participants by then. The session will happen in the robot room where I will be providing them with more information regarding the workflow, aim of the experiment as well as handing out the forms to sign and participant information sheets.

06.10.16

Conversation is started with Dr. Steve Wright author of the paper "Exploring Actor-Network theory and CAQDAS: Provisional principles and practices for Coding, Connecting and Describing Data using ATLAS.TI" to get his insights regarding which qualitative software to use for this research. He is a specialist in both atlas.ti and Nvivo and trains people to use both.

He offers training for both and recommend due to the methodology of the proposal to use atlas.ti. Different funding options are discussed (doctoral academy, wsa, research methods week) to bring him to Cardiff. He agrees to send a personalised training plan in case there is not funding to put together a bigger group.

12.10.16

Waiting for participants to come into the robot room. Open-door policy from 14.00 to 22.00 for them ask any questions, read the information sheets, answer an initial set of questions and sign up.

14:05 – participants start to show, they are coming in groups of 3 or 4 to ask for information and sign the forms. I decide to keep the groups in which they came for the first two sessions when they will be introduced to the more general software workflow and robotic interface. Participants that come on their own can join a 'group' keeping a maximum of 4 people per session to ensure that is a personalised introduction.

After an explanation of the aim: to create a concrete shell the workflow is explained: Maya design to do patterns and simulate them. Paths are then moved into the Alice platform for robot to cut. Once the pattern is cut the concrete will be hydrated by the participant and mounted into a wood frame (provided by the researcher).

The second stage of the task begins when the robot will be pushing the material into place and scanning it to send information back to the designer who will compare the received point cloud to his design and decide how to proceed. The feedback loop will continue until the designer is satisfied. Participants in general don't have many questions after this is explained, they read and sign the forms and groups of 4 are formed to start with the introductions the following week.

18.10.16

09.15 am

The health and safety form are discussed with Wassim, he agrees that most issues are covered but asks to add a note that masks and gloves will be provided for participants when handling the material. Stress to be avoided by limiting the sessions to 2 hours. Participants are going to be asked to wear hard shoes in case the wooden frame or a tool falls in their feet to limit the potential for injury. All the other health and safety risks are covered by the risk assessment of the robotics lab.

He is notified that 28 participants have signed the form and is agreed that it is a good number.

The training plan in the use of atlas.ti as a platform of computer assisted qualitative software for this research is signed by Wassim and submitted to Katrina for approval.

17.00

The first group of 4 participants CS2-002 (Nik), CS2-004 (Epa), CS2-005 (Sim) and CS2-006 (Jac) (2M, 2F) came to start their design process. Initially we agree to meet in the robot room where they are introduced to the robot (robot is off for this day) and had an explanation of reference frames and how they affect the movement of the robot.

They didn't ask many questions; the topic is difficult to understand without jogging the robot so we will go deeper on this next session.

The concept of a cross product was briefly explained as important to any procedure related to robots and as means to control the orientation of the robot tool center point (TCP) this independently of which tool, software or design they are doing.

After this, the group moves to the PGR meeting room to use the screen. Participants were briefed in the design and simulation process for the ncloth (1st stage of the experiment which is to design something). The simulation parameters for the ncloth to behave as concrete canvas are shown, explained and distributed to the group. This particular simulation -different to the minimal surfaces that participants have been doing- need from a different kind of constraints to be used. This was mentioned, emphasized and the differences between constraints explained.

The concept of a locator was introduced and why they need to be tangential to the curve as they defined the orientation of the tool.

2 Mel scripts were shown: one to create locators tangential to the curve and a second one to export the points so that they can be used in the robot simulation platform (Alice)

Participants concerns were regarding if this method was particular to this design process or if knowing about it will allow them to use the robot to do different designs and processes that they might want in the future

Participants CS2-004 (Epa) and CS2-006 (Jac) were asking questions mainly regarding the software as one of them has not used Maya before and only 3ds max. In general, they seemed engaged. Participants CS2-002 (Nik) and CS2-005 (Sim) were mostly quiet.

Participant CS2-004 (Epa) got interested in the fact that they are designing 2D patterns without knowing the outcome rather than designing the 3D shapes as usual design processes. This is an important part of the system. The system was then explained as well as hoe the offset between curves and joint size affects the result.

The reward is discussed and logistics for doing it on a Friday as it seems the day that suits most of the people. They will like for the trip to take place before their studio trip so that they don't have to pay transport to London. The idea is considered.

The session was finished, participants took home a Maya file with the ncloth parameters and the scripts to place locators along the curve and to export the locator positions (12 numbers) to a text file.

19.10.16

The second group with participants CS2-015 (Velis), CS2-003 (Val) and CS2-021(Pa) are introduced to the robot and the workflow of the task. In this case we start inside the cage where they can see and touch the previous prototypes. The cutting tool is demonstrated and why it is important to keep its orientation tangential to the curve as otherwise it won't be able to cut. A brief explanation of the cross product and how to obtain it to orientate the locators is offered using a small plastic reference frame. Participant CS2-003 (Val) said that she has previous knowledge in using the cross product and understands its meaning.

The raw material is also shown and they are allowed to touch it in its dry state, from here all its different properties: the duality between its initial soft, fabric like condition and final rigid state and how by hydration it starts to cure offering us a 3-hour window opportunity to manipulate it before it becomes stable are explained. After these 3 hours the concrete needs to be left for 24 hours to achieve its final rigid state. If the concrete is manipulated after this period it will break.

The patterning system is explained and demonstrated using the different pieces in display: how the staggering and size of the cuts and joints change the final result. Participants have questions regarding the boundaries which is explained they can play with it as long as it fits inside the 30 x 40 piece and it has to be fixed physically and in the simulation.

Movements of the robot are explained and how each axis moves only in one axis but all together give the 6 degrees of freedom. Participants CS2-003 (Val) and CS2-021(Pa) are concerned about not using all the degrees of freedom that the robot offers and they ask for examples of tasks where the robot uses all its degrees of freedom. To explain the differences with 3dprinters, CNC and other 3 axis machines, the researcher explains the rotational capabilities of the robot and this didn't seem clear so a decision is made to turn on the robot and jog each axis to show how they each move independently in its own reference frame.

After this the group moves out of the cage towards the computer area where the simulation software is shown. By looking at it and moving the axis digitally the mechanics of movement of each axis is better understood by the participants. This also starts a conversation about what exactly are the instructions that robots need. The researcher explains that the robot only needs points as it doesn't care for much else, as a matter of fact he is unaware of anything but his own body. The only information that the needs is the position and orientation of its tool. This explanation is taking further by telling the differences between forward kinematics where the rotation of each joint is sent to the robot and inverse kinematics where only the TCP position and orientation is sent. To make this idea clearer to the participants they are shown two pieces of code, one coming from the kuka prc which is sending tcp location and orientation (IK) and one from the Alice platform which is sending position and rotation of each joint (FK) how the robot solves each case is explained.

After finishing this demonstration, the group moves to the DTP room to show the Maya workflow using a big screen. In this case, rather than drawing a set of curves, participants are shown to draw curves and offset them. These curves are then rebuilt and points are deleted to make for the joints. In a third step the curves are projected into the mesh and the mesh is cut with them before converting into Ncloth for the simulation.

The ncloth simulation parameters are explained and the different types of constraints that can be used, which is different from what they are currently doing in their class.

They are shown how to do a locator and how it can be orientated tangential to the curve as well as the right-hand rule. Participants seem to feel comfortable about the workflow and one of them has problems and questions regarding the software install which are addressed by another participant from a higher year who had similar problems.

Participants leave the 2-hour session with a Maya file that that the parameters for the ncloth simulation and a PowerPoint with step by step instructions from curve generation to converting it into ncloth and further simulation.

19.10.16

Conversations to order the material start with concrete canvas. They offer a discounted price in what they call their 'B-grade' material which might have some slight cosmetic staining or doesn't have the minimum density of concrete required for more demanding applications. They can offer us this material for £10 a metre, whereas the standard CC5 (5mm concrete canvas) has a price of £25.30 per square metre. The material is supplied in 1.0m wide rolls and has a weight of 7kgm/sqm.

It is decided that the B-grade material should be ok for this experiment. 9m are ordered considering that each participant will design a 30 x 40 cms piece and it will be built two times: one using the robot and one using a traditional digital workflow: contours of the final shape will be laser cut and the fabric will after be extended over it.

20.10.16

An invoice is sent by Vladimir from concrete canvas for the material and it is paid. He will deliver the material himself on Monday after work as he lives in Cardiff. Due to stock it is agreed for the 9 meters to be delivered in one 5m roll and one 4m roll.

Katrina informs me that the CAQDAS atlas.ti training budget has been approved. Now I have to agree with finances the best way forward and with Dr. Steve Wright to set the dates for the different sessions to start coding the research results.

24.10.16

Participant CS2-002 (Nik) has been having problems downloading and installing the software she gets in touch and we install a previous version which works perfectly in her machine after testing the files.

Participant CS2-006 (Jac) contacts me during a trip to the café in Bute, he is making his curves in grasshopper and importing them to Maya for the simulation. The curves are not working. We meet inside the robot room where he brings his laptop and we fix the problem. The problem is due to curve history and off-centred pivot as they are coming from rhino. I show him how to fix these two issues and the workflow is running again.

The third group of participants arrives at 16.00 for their introductory session. The group is made of participants CS2-017 (Jan), CS2-018 (Bart), CS2-026 (Gian) and CS2-027 (Alex). The procedure is the same as with previous team from the 19.10. Introduction starting inside the cage where material is shown and design constraints explained as well as robot behaviour and constraints. In this case the robot remains off and axis movement explanation is done using the software simulation. After the software explanation the group moves to the PGR meeting room where the digital tutorial takes place.

The group is generally scared of the robot and when asked initially to come inside the cage to look at the concrete prototypes and end effectors they are hesitant and remain outside or very close to the door. They have to be encouraged to come in and make laugh a little by making fun of their fearful attitude towards the machine. After the design explanation participant CS2-027 (Alex) asks an interesting question:

CS2-027 (Alex): how do we know what structure will result?

Alicia: that is why you have to do a simulation of your pattern and why we are using the digital platform otherwise you would need to test them manually until you get an intuition of what works and what doesn't. I have been working on it for some time now and will provide you with the simulation parameters that will allow you to test your design very accurately. After doing a few ones you start to get an intuition over the material and what works.

CS2-027 (Alex): What are the correct parameters for a successful pop-up geometry, related to the distance between edges? (cuts)

The researcher holds one of the prototype models and encourage participants to hold it. This to show that the distribution between cuts has to be around 1cm if less when you are cutting all the cement and the material becomes very weak as it is only fabric, on the other hand if the cuts are too far apart, they will not counter the material stiffness hence the pop-up will be very shallow. Researcher holds a piece of the material without cuts and encourages participants to feel it. This to show the stiffness of the material without cuts and reinforce the idea that the pattern allows it to pop into predesigned shapes but if cuts are clustered together it results in concrete loss and hence weakness. The horizontal distribution of joints is also re-explained as crucial for the popping. But there are no 'correct' parameters as it is a system that allows for a range of options.

There are no more questions and the group move outside the cage to see the software simulation software and the locator positioning with the curves.

Participant CS2-026 (Gian) asks: How will the robot know where to go next?

Alicia: Very good question. He won't and it might not cut the curves sequentially as they are numbered according to their creation and cutting order. We need to duplicate the locators or points at the beginning and end of each curve segment and move them up on the 'z axis' so that when the robot moves between points it doesn't cut the material. This is further illustrated using hands and the end effector showing how it will cut then go up move to a different position maybe having to go across the material or to the curve segment next to it and it will then go down to cut, this gets repeated for each curve.

This is reinforced by showing a rhino file where all the curves are converted into points for the robot to follow and showing a second layer that lies above the first one where only the starting and end points exist. This is imported into Alice and the simulation is run.

There are no more questions so the group moves towards the PGR meeting room where the explanation of the digital design process takes place using the screen as with the other groups of participants. Questions during this part are mainly involving technical issues and where to find things. Participants are told not to take notes and rather pay attention to the screen as a PowerPoint with a step by step explanation of the process will be provided before they leave. The group leaves after copying the 3 files given to all (robot room, setting for ncloth and ncloth edge, power point with step by step instructions of all the process)

25.10.16

Participants CS2-002 (Nik), CS2-004 (Epa), CS2-005 (Sim) and CS2-006 (Jac) arrive for **second session** (recorded). Intention: to start creating a relationship between the human and non-human actors involved in this research. Human actors are **introduced** to their non-human partner (how to code him and all his parts: size, colour, end effector, Kinect for feedback, Alice software programming, scripts for code generation) for this design process. Participants seem uncomfortable with the robot, they all remain next to the cage walls and seem very shy to move forward, the robot is in teach mode and they are encouraged by the researcher to come closer to the robot but they remain in the edge.

The fact that they came in a group and not one by one allows them to joke with each other (relax a bit), make fun and pass the teach pendant around while laughing. During the whole exercise and explanation none of the research participants ever left their place next to the cage or ventured anywhere near the robot.

The session starts with an explanation of the teach pendant as a communication tool between the humans and the robots. The researcher also describes how the teach pendant is used normally in factories and how robots can be programmed through it, normally in a factory setting through teaching the target positions and then modifying the code to add loops, etc.

Participants jog the robot and then they receive an explanation on how to record a program. They proceed to record their first robot program- online programming- (with this group we didn't run it in auto mode)

Participant CS2-006 (Jac) is very outspoken and volunteers to do a program but ended up doing movements with very little variation between them. Was taking his own pictures during the experience and more concerned with the digital workflow. When manually recording his path, he leaned to see if the end effector was touching the table and squatted, all of this from his position next to the cage. The researcher mentions that is possible and necessary to take a view from a different angle as the tool can easily be angled so he might want to go around but he doesn't leave his place.

Participant CS2-005 (Sim) quite risk taking and adventurous, was the first one to volunteer to jog the robot and after doing some initial moves move into full speed (of manual mode – 10% of real speed). Recorded a program more adventurous trying to get the robot close to the other participants but never left her place next to the cage or went anywhere near the robot. A very outspoken participant. None of the participants decided to move around the robot or left their position near the robot cage through the whole task.

Participant CS2-004 (Epa) asking many technical questions: how do I record a point? giving the idea that he was confused but in fact did the task well

Participant CS2-002 (Nik), very quiet but the most efficient. Simulation was finished nicely and was the last one to use the pendant and record a program, but who did more aggressive moves using all the robot joints to reach each point and purposefully looking for creating situations of twisting and contortion between joints at each position.

Conversation end with questions regarding the 7th axis and its influence in the robot behaviour. Participants were interested in knowing how the 7th axis works and were it is positioned in relation to the robot. Examples are given of tracks, turntables and robots hanging upside down in gantries with the material in a track.

26.10.16

14.00

Second group of participants that comes for their second session. Participant CS2-021(Pa) cancels his participation on the research exercise. The session progressed with the remaining participants: CS2-015 (Velis) and CS2-003 (Val).

First half was dedicated mainly to solve their technical problems for the digital design process and talk about their design idea. Participant CS2-015 (Velis) had mostly technical problems with shattered curves that won't actually be cut. Participant CS2-003 (Val) didn't develop any design, but had several ideas about doing a hyperbolic shape. These where discussed as possibilities but not certainty regarding if they would work but it was agreed that they would make for an interesting test.

On the second hour, we moved into the robot cage (recorded). Participants are less afraid than the previous group and come straight to the machine rather than remaining on the sides of the cage. They are introduced to the teach pendant and the different ways to move the robot (axis, world, tool, base) the differences in term of reference frames and moves were shown. Both participants jogged the robot and a 'target' was placed so they can experience the difficulties and advantages of each movement type. This also allowed them to better understand how you need all of them and to be continuously changing between them to achieve a position.

Participants were interested in knowing if the robot will move following the exact same moves, they went through when they are jogging him into position once the points are recorded and it has to reach them by itself (interesting parallel to the Brazil CS01 where participants felt surprised when the robot wouldn't follow the same path they did when recording the points). Participants had questions regarding which path will the robot follow and how it is related to how it is recorded. Researcher explains that there is no relation, normally you can move between the different robot movement types (axis, world, tool, base, etc) to reach a desired point, once they are recorded the robot will interpolate between the recorded points following the path that its IK consider more optimal given the different TCP recorded positions rather than following the convoluted moves that you did to reach and record those positions.

After this they were shown how to record a program, two new objects are placed on the table as 'targets' that the robot needs to touch and they need to record in their program. Participants were risky taking the robot end effector to almost touch the table, they achieve all the targets through very convoluted motions and tested how the robot reaches them with less moves once they are recorded (a straighter path is preferred by the robot and this is explained to them). It seemed like they were having fun. Participants remained close to the robot for the whole duration of the task and didn't hesitated to move around it to check if he was reaching the tip of the 'targets' and squat next to the table.

Participant CS2-003 (Val) is asked to move a bit from the side of the robot as participant CS2-015 (Velis) is recording her path and not to be close when the rig is moving even if it is in teaching mode.

Participants CS2-003 (Val) & CS2-015 (Velis) struggled using the teach pendant to play their programs or jog the robot, they will either push too hard and the robot won't move or they will push too soft. When running their own programs, it was worst, they couldn't run the program smoothly due to constant differences in the pressure applied to the grey and green buttons (running program in teaching mode) and the constant pauses that this causes in the movement.

Both participants CS2-003 (Val) & CS2-015 (Velis) asked again about the steps of the task. The researcher explains that the cutting part will be automated and send from their initial curves by getting locators and aligning them tangential to the curve so that the cutter works, whereas the second part will be done by sending the pushing points, scanning, analysing the feedback from the robot and sending a further set of points until the digital and the physical shape match. They show an interest and say that they would be more interested in doing the second part of the task by **jogging the robot after receiving the feedback to the areas where it needs to push more rather than sending a new set of points through the computer**. Interesting proposition to be considered during the execution of the task.

16.00

Group of 3 participants CS2-007 (Chen), CS2-009 (Vel) and CS2-012 (Ele) comes for their first session. We start in the robot room outside the cage where I explain the objectives of the task. This group is more interested in the digital, technical and software aspects of it and declines going inside the cage. I bring the concrete pop-up objects and both end effectors out of the cage, we do all the explanation sitting around the computer in the robot room and my computer is open to show the new software version developed for the robot plugin.

An initial explanation is made regarding the nature of the material is duality and how it is soft when we cut it, after hydration there is a 2-hour window before it starts to cure that is going to be used for the pushing process with feedback. After this the group was introduced to the software workflow, they got an insight into the software developed to send the positions to the robot, the scanning code, and they tested how the robot goes through each point and how to remove the background noise from the scanned piece through the developed code.

An explanation of the differences between Inverse Kinematics and Forward Kinematics was made and the differences between sending one or the other. They also saw a piece of code from the KUKA PRC sending the TCP positions and a piece of code from Alice sending the rotations for each axis to emphasize the difference between both.

Due to the nature of the tool that we are using for cutting the orientation is very important, this was explained as well as the notion of cross product and the difference between the previous version of Alice that only used positions and the new one that takes planes was shown. They asked questions regarding why do we need to send 12 numbers in the new version rather than 3 and how does the robot know or interprets them. This prompts the researcher to show how older versions only have points, whereas the new one has coordinate frames for each point and go deeper into the explanation of the cross product and aligning the planes or locators in the case of Maya tangential to the curve to send the correct orientation of the tool for each position to the robot. The group seemed satisfied with the explanation and the visual information about the different feeds. Additionally, by dragging the circular cutter along the table is possible to emphasize the fact that if the orientation is wrong it can go through the correct points but won't be able to cut, whereas if the orientation sent to the robot is tangential to the curve it will be able to cut. The explanation with this group becomes more technical in terms of maths and the robot code compared to the other groups that have passed. This is a reaction of the researcher to the questions and overall behaviour of the group.

After this the group proposed to remain on the robot room around the laptop for the digital design workflow explanation but the researcher insisted in moving to the meeting room so that they can see the software and the different steps in the screen. The participants agreed to this move.

The second hour is spent explaining the digital workflow, participant CS2-009 (Vel) has used the software before but not the other two participants. A detailed step by step explanation is given with the aim of streamlining the steps and not making it confusing or stressful for participants. The explanation is very straightforward as they seem to feel comfortable with the steps and procedures. It is emphasized that they don't have to know the software and can achieve the result by just following the steps, the design task is limited to drawing a set of curves, the files, simulation parameters, constraint parameters are given to them. They are also given the option of just doing the robotic task without designing something themselves so that they avoid this first part. If they select that option, the researcher will provide a design for them. They decline the offer and seem motivated to develop their own designs. The session ends after agreeing for a date for their next session, introduction to the robot, and giving them the Maya files with the simulation parameters as well as a power point with all the steps.

18.00

The third group of this evening, participants CS2-001 (Char) and CS2-019 (Anas), come for the first session of the robot task. We start in the robot room outside the cage where the properties of the material, constraints of the system and thinks to look-out when developing the design are explained. i.e. size of the joints, size of the cut, distance between cuts. The idea of designing the 2D without knowing the 3D causes concern in the participants, especially as to how will they know if the result is successful or if it will fail. This is explained that through the simulation they will know whether it works or not. They are also offered the option of not doing the design and just the robotic task if they feel overwhelmed by the situation.

The different software workflows are shown to them, from Maya to Alice and the scanning through processing. An explanation of the technicalities of sending points vs planes and the difference between forward kinematics and inverse kinematics is provided but they don't seem to engage as much with it. The end effector is also explained and why it needs from planes rather than points. This group expends the shortest amount of time in the robot room (30 mins) and doesn't ask any questions.

We move into the meeting room to show the design workflow in Maya. Both participants are unaware of the software so the explanation is highly detailed and long. This also allows me to add more details about the workflow into the PowerPoint that previously were taken for granted, instructions become more specific regarding which menu to click and were to find it.

Participant CS2-019 (Anas) wants to test options and not only do one piece, she is encouraged to do it but is reminded of not getting stressed nor overwhelmed by the task and that help will be available and provided as needed. The offer of giving them a design so that they only do the robot task is reiterated and rejected. The session going through the software workflow becomes very long for this group due to the amount of detail going into each step. The session ends by providing them with the files and scheduling the next one which they are reminded will be shorter and less intense software wise as it is only about the robot.

28.10.16

The format of the introduction session tested with the last two groups on Wednesday will be used with all the groups on today's session. The format and sequence of the session is described below:

The groups don't go anymore inside the robot cage to see the end effectors and previous material studies. Both end effectors and previous material prototypes are around the computer.

The researcher would be seating in the computers' desk facing the group, with all participants seating around. The explanation starts with a description of the concrete material that is going to be used a dry sample is available for them to touch and the pop-up prototypes. During this part the constraints of the system in terms of the cuts and joints and the dimensions for it to work are explained and also shown through the prototypes. Participants are encouraged to touch the prototypes and feel the difference when the distance between cuts is too little and all the concrete has come out during cutting – the material feels soft- this to be compared with situations where the distance between cuts is larger, hence a thicker section -full of concrete- which then becomes very rigid remains inside.

Successful and failed prototypes are discussed in terms of the 2D pattern that has to be designed and its influence towards the different results. After this the end effectors to be used and the robot are discussed.

The explanation starts by describing how the robot differently from other digital fabrication machines that have a specific use, robots are useless after purchase until and end effector is designer. This means that a range of tasks are available for them to perform as long as we are clear about our objectives and design the appropriate tool for them. After this a demonstration in the computer using Alice's kinematic solver is done to show how each one of the different axis moves. The need for the robot to coordinate all the different axis to reach any given position is emphasized. The lack of an optimisation feature for robotic paths is explained in terms of the different tasks that they can perform and how optimisation can be done for speed, torque, etc. Additionally, the different ways in which it can reach the same position are described using the researcher hands and arms movements (add diagram).

An explanation of maths and the concept of the cross-product follow to show how the robot defines the position of the tool, this is illustrated using the KUKA orange reference frame and the cutter. AS the end effector is a cutter that has to go tangential to the curve, the role of orienting the planes aligned to the curves and in the direction that we want the robot to approach them according to the different tools is emphasized. The researcher describes how this is important knowledge not only for the task to be done now but in general one of the main things to do when working with robots. The concept of Tool Center Point (TCP) is referred and how this will be a common work whenever they work with robots as the defining the orientation of the TCP can have huge implications with some end effectors. After the theoretical explanation, the group is shown locators positioned in a curve in Maya and then sent to the robot simulator only as points (center points). The simulation is run so they see how the robot approaches them in unexpected ways, this is compared to locators oriented tangential to the curve and all the 12 coordinates of their orientation sent to Alice, when the simulation is run they can see how the robot approaches them with the tool following the specified orientation. A physical demonstration going through points with the circular cutter perpendicular to them and its inability to cut versus when the cutter is tangential to the curve and it can cut is shown. The groups are made aware that if they are using a different software such as Rhino and its plugin grasshopper, they will be orientating planes, in Maya this are locators, and the names will change but the concept is the same.

Keeping with the same topic, the groups are explained the difference between Inverse Kinematics, traditionally used in robot programming, and forward kinematics. To illustrate this the researcher uses hands and arms that show how given a final position different way of arriving to it are possible. This is followed by a description of how different robotic companies have their proprietary kinematic solvers but they are based in the same matrices. This is tied to the sometimes 'unpredictability' of industrial arms as they might choose a different path from the one though or predicted in some custom-made simulators which can potentially endangered unaware objects in close proximity to them when the rig is moving. To conclude this they are shown a .src file containing the final x,y,z positions and a,b,c, rotations on the screen (from the kuka prc plugin for rhino grasshopper) and they are invited to compare it with a .src file sending the rotations for each axis (from the Alice software) and how they understand the differences on the robot behaviour from each. There is emphasis in not one being better than the other but different.

Using a combination of the researcher laptop and the computer in the robot room the workflow of orientating the locators tangential to the curve, exporting their positions, and importing them into Alice for the simulation is shown. It is pointed out through the robot simulation how the reference frame of the end effector orientates following the orientation of the locators.

The next step of the workflow is described, once their curves are sent the robot will cut them, then they will hydrate the material and mount it into the frame, as a reference they are encouraged to see the wooden frame with the shell hanging that is in the robot room.

The second end effector with the sphere in shown as a tool to push the material into position and the Kinect to scan the resultant deformation. The researcher describes how after scanning the point cloud will be taken into grasshopper and through the volvox plugin compared to their digital simulations. As some participants from previous groups have not been familiar with the meaning of a point cloud, for this groups the Kinect is turned on and the scanning process as well as the processing script to reduce the amount of background is shown and they are encouraged to interact with it.

After the explanation is done, they are asked for questions and the second stage in the PGR meeting room starts. Before starting participants are encouraged to interrupt at any point and if they are going to follow in their computers to stop the researcher whenever they run into a software difficulty.

During the second hour that takes place in the PGR meeting room, the researcher computer is connected to a screen to project the information.

First, they are shown a Maya file with the robot room on it and the Maya layers explained. They are asked to keep the robot and the table in a locked layer to avoid accidentally moving it as all the workflow is calibrated considering the centre of the robot base being in the 0,0,0 position. This is shown by rotating the model so that they can see the origin of the file being the origin of the robot.

Secondly, participants are taken step by step through the Maya workflow of: plane creation according to size, curve generation and rebuilding to fix curvature and even-out distance between vertex, curve offsetting or scaling if the design is not concentric curves, curve detaching to create the different cuts, rebuilding of curve pieces to even out the number of vertex, deleting of vertices to create the 'joint' areas. During this explanation the Maya file is described as a scene and the objects as they appear in the outline as actors (I randomly mentioned this last session and it seemed to help when explaining how after detaching a curve, new curves – the detached ones – appear into scene in the outliner)

Once they have their set of curves, they get cleaned and history deleted. The plane is displayed again for curves to be projected on it and finally the plane will be cut using the curves and edges detached for a resultant pattern of detached cuts.

Finally, the plane is made into an nCloth the setting for the nCloth and for the edge constraint are show. They are also made familiar with two different workflows to get rid of the faces between their new outer edge and the edge of the plane.

Sessions finalise by asking the participants if they have any questions and providing them with the two Maya files: one with the robot room with the location of the table and one with the setting for the nCloth and its constraints. They are also provided with a power point presentation that describes the process step by step.

10.30

First group of the day comes for the training 3 participants share the same nationality - CS2-010 (Kat), CS2-011 (Mar) and CS2-022 (Pro)- and are very comfortable amongst themselves. The fourth participant in this group CS2-020 (Soo) is not part of their group dynamic so the introduction has to start quickly. The group doesn't have questions regarding the robot operations, vectors or different ways of robot movements. They are interested in the process and most their questions are geared towards the constraints of the design system, space between joints, connections and how they affect the pop-up outcome. They also enquiry about the material properties. Participant CS2-011 (Mar) express that she feels braindead after the robot explanation and before moving to the PGR meeting room for the digital design workflow. All participants on this group decide to take out their laptops and follow the design exercise step by step. This results in a lengthier explanation of the design digital workflow as they are following each step in real-time and the explanation is stopped when they run into particular difficulties of not knowing where a command is, or the software not behaving as the one in the screen All of this is sorted-out during the training process which might be better than when they just listen to the explanation to do it themselves later. The participants leave with a half-made design following all the instructions.

14.00

The second group of participants arrive for training: CS2-023 (Har), CS2-024 (Ah) and CS2-025 (Efst). Participant CS2-025 (Efst) has a very good question regarding the radius of curvature possible for the blade and its influence in the pattern. This is something that hasn't been mentioned before neither ask by any other team but it is an important parameter to consider during the design of the curves.

The group is concerned about the possibility to do the curves in rhino / grasshopper (which is a platform they feel more comfortable with) and import after to Maya which is acceptable and will totally work, even if it provides a different workflow which will require from an extra step.

16.00

Last group for this day, made of participants: CS2-028 (An), CS2-016 (Mic), CS2-014 (Iv) and CS2-013 (Nad)

They seemed comfortable with the software. Participant CS2-028 (An) had questions regarding the concrete resistance and how much can it bend before breaking if they do big cuts.

Participants CS2-028 (An), CS2-016 (Mic) and CS2-014 (Iv) engage in conversation about adding sensors to the robot to know his position rather than calculating the IK and FK. The researcher explains that even if you have sensors the robot has to internally calculate its movement to know where to go. Is interesting that they start to ask questions regarding the kinematics and how can the robot feel and sense its environment as well as the material properties rather than only technical questions regarding the software.

They forget about the simulation step and ask how will they know which form will result from their designed curves. A: that is why we are simulating them in order to know and get an intuition of what will the resultant shape be.

The explanation regarding the robot reference frames seems to get them interested.

30.10.16

A google group is created with the aim to engage discussion and questions from all participants. The initial conversation is to schedule the dates for the trip to London as they don't seem to suit everyone. A new proposal to change it for the 20th emerges and it seems more convenient to everyone's schedule.

Now conversation and negotiations with the architectural offices start in order to change the dates.

31.10.16

Video tutorials step by step for the curve preparation, simulation and export are prepared and uploaded to the google group. All participants have access to this material and can do the training and design exercise in their own time.

04.11.16

11.00

Third group of participants scheduled for the second session: introduction to the robot. Participant CS2-027 (Alex) postponed due to personals reasons. Participant CS2-017 (Jan)was not feeling well and also asked for it to be re-scheduled. The session is then done with the remaining two participants - CS2-026 (Gian) and CS2-018 (Bart)- from this group of 4 (first session)

The first hour is used to fix software problems regarding the curve generation in Maya and the simulation of the pop-up exercise.

After this we move inside the cage and proceed with the robot introduction, explanation between the different modes of operation, the teach pendant and its role for robot programming and the different axis. I place 'targets' on the table and they have to reach them using the different movement modes of the robot to test approaching them. Participants don't like neither feel comfortable with the teach pendant. I explain the difference between online and offline programming to discuss the importance of the use of the teach pendant for more general robot tasks and applications. The discussion includes why the teach pendant is not so useful for architectural applications where we don't know the location of things in 3D space.

Participant CS2-026 (Gian) has several questions regarding the reference frames and how the robot knows where he is, he also is curious about the tool reference frame and why it goes down when the z positive is pressed. The explanation is done in a different way with the aid of the orange KUKA reference frame and by changing the way the robot moves, the participant seems less confused and expresses an understanding of how the robot moves by the end.

Participant CS2-026 (Gian), also asks how do you use the different moving modes and why? Or if using them makes a difference in the final program. The explanation is done using the robot and the targets by showing him how you can accommodate the tool using the axis mode and then use the tool mode to move the robot up and down and showing him different ways of reaching the targets and how some positions are easier to achieve in axis mode whereas others are less intuitive and easier to achieve in base or tool mode. There is an additional explanation about how the robot will not reach the points in the same way as they are recorded and if there is an object in the middle or something that he avoids while recording but doesn't record the robot will crash with it when executing the program.

Both participants tried reaching the 'targets' with the robot. After this an explanation is done of how to record and play a program.

Both participants are initially shy and remain at the edges of the table while moving the robot but they slowly start to get more comfortable and squat or approach the robot from different positions to see how the tcp is getting orientated and rectify its position.

Participant CS2-018 (Bart) is more practical and delivers a clean, straight-forward program of the robot reaching each target with a straight tool. Participant CS2-026 (Gian) takes a lot of more risks by getting the robot very close to the table and positioning the tool in very acute angles when reaching the targets. He makes an interesting program with a lot of angle changes. When they run the program, they realise - especially in the case of the acute angles- how the robot doesn't do all the moves they did to achieve the same positions. The session concludes by all of us getting out of the cage and running the programs in automatic mode were the speed becomes more impressive.

14.00

Meeting with Dan at the workshop 2+ hours to figure out logistics for the **Kinect end effector** (another **actant**). The Kinect camera has to be aligned to the centre of the flange of the robot so that the origin of the point cloud and the x, y, z position of the flange can be aligned with less transformations. This means that the Kinect shouldn't be centred to the flange but thrown towards the back. We also talk about the best way to hold it in place without gluing it as the robot flange will be rotating as it changes between pushing and scanning. A solution with two sticks at the front inside a tight case and foam is decided.

07.11.16

Day making **wooden frames (actants)** for the concrete to hang. This includes cutting the wood to an appropriate size, gluing, drilling and putting screws in the connections. The day also included the manufacturing of the end effector with the Kinect attached to it for the scanning process.

08.11.16

Wooden frames part 2, tool calibration and height. End effector for Kinect. Blades and foamboard so that we can cut the contour of each participant and mount into a general board from the size of the frame which will be stapled to the edge of the frame.

09.11.16

AM (**description of the design exercise**)

Development and fine tuning of the **grasshopper definitions (actants)** for the pushing and comparison between the initial point clouds as well as for getting the new material positions to compare and generate further pushing iterations. The length of the newly developed Kinect end effector has to be included. Also, each plane rotated 180 degrees upon itself so that the robot rotates the sphere at each point to 'massage' the fabric. After scanning the Kinect is translated to the 0,0,0 of the point cloud in the processing script. The locations from the point cloud are exported as a txt file and imported into Rhino. The point cloud is translated from its origin to its position in world coordinates on top of the table. The point cloud from the original simulation and the point cloud from the scanning step are compared. A new set of points is generated from this comparison between the digital and the physical model. The new points are sent to the robot for another pushing iterations. These steps are repeated until the physical model and the original simulated/expected result converge or until the participant is happy with the results.

The **third session** is planned as one where participants will first use **3 MEL scripts (actants)** to convert their curves to robot code for cutting: One that adds locators tangential to their curves based on a specified number of spans; A second one to move the first and last locator in each curve up on the 'Z' direction so that the robot moves in the air in-between curves and a Third one that exports the x, y and z location of the origin of each locators as well as the x, y and z of the X of the Y and of the Z coordinates of each locator (12 numbers in total). This information can then be fed to the **robot purpose made kinematic solver (actant)** to generate the robot code. Participants will then cut the fabric with their curves, hydrate and hang it in the frame. While they do that, I change the robot end effector from the knife to the Kinect with the sphere. Participants, then place the frame in the marked position in the table (for point cloud translation purposes) and proceed to deform it, scan it and compare between digital/physical as well as the different states of the physical model using the **processing and grasshopper definitions (actants)**.

For the first deformation pass, the deformed mesh from Maya is imported into rhino. A model that contains the wooden frame in the same location with the robot and the room is used to visualise the translated scan. A grasshopper definition is used that generates a grid of points and projects them to the mesh. Around each of these points two frames are created: one for the position of the sphere and a second one on the same origin but rotated by 180 degrees for the robot to rotate around each point 'massaging' them. The coordinates of this frames are then exported to the kinematic solver where the robot code is generated and loaded into the controller for the initial pushing.

Participants can do this step manually if preferred. In terms of the digital workflow given that they provide their mesh all the process is done for them and they only need to hold the teach pendant while running the deformation program, as this is not run in automatic mode to allow them for more control.

After the first deformation, participants rotate the end effector to a position where the Kinect can scan and the processing script is used for the Kinect scanning process. The script allows them to control the depth of the scan using the keyboard arrows and remove background. It also places the Kinect position at the 0,0,0 of the point cloud so that when exporting it, the point cloud can be translated and rotated using the position of the robot end effector as its 0,0,0. The point cloud is exported from processing as a txt file which is then imported into rhino grasshopper.

The point cloud from processing is then imported into the rhino file used for the first deformation pass, where their deformed mesh is already loaded and two grasshopper definitions are used: the first one needs the designer to input the current position of the robot end effector – this is taken from the teach pendant- and with this information it translates and rotates the point cloud first into rhino coordinates and then to the position of the frame in the digital model. The point cloud is further cleaned to remove extra points corresponding to the frame or to other elements from the scene and moved into the second definition. This definition takes the mesh from Maya as an input and projects the points from the previously cleaned point cloud into it. Points within a range (further from their expected final position are isolated) two planes are created around these points: one for the sphere to touch and its inverse for it to rotated and massage those areas. The coordinates of the planes are then exported to the kinematic solver where the robot code is generated and loaded into the controller for further pushing. This last step is to be repeated until the designer is satisfied with the result.

4.00pm

Participant CS2-015 (Velis) arrives for her final robot session. The MEL scripts are not working properly on her machine as empty locators are being created which results in problems when exporting them to generate the robot code. I try to fix the problems in the script and the participant tries with a new set of curves. The session results in 2 hours of the participants doing a lot of manual work to get rid of the empty locators that are being created by the script before moving them up in the z axis. We are not able to export any coordinates to generate the code for the robot. I apologize at the end of the session and ask her to send me the curves to me so I do this job for her after fixing the scripts. We schedule a 4th extra session for the actual development of the robot task.

6.00pm

Participant CS2-006 (Jac) arrives for his final robot session. The scripts while working on my machine are not doing it on his. After 2 hours of cleaning the model and the code the participant manages to send some the cutting code to the robot. The robot is doing a lot of 360 degree rotations as it is going through his curves, this has to be fixed by adding a constraint to the code which checks for the difference between the current point and the previous point, if that difference is larger than 180 it subtracts the current point from 360, this with the aim of having the rotations to the 6^{th} Axis always going towards the same direction and avoiding the continuous rotations caused by big changes in the angles. This helps initially but there are points that still need to be fixed and a further constraint is added to the code. It starts to look better but the session has been going on for more than 3 hours. I ask the participant to leave his locators with me as I will fix all the code and we schedule a 4^{th} robot session for the actual development of the task.

After participants leave I am concerned: first over the code not working in their machines, or it running into all kind of weird behaviours and secondly about the possibility of them getting frustrated with the task and finding it too tedious because of the problems with the code.

The MEL script is generating void objects due to an uneven distribution of points in the curves, once all of them are rebuilt and the distribution of points is even it works. The robot code works by adding two more constraints checking the difference between the current position and the previous position and if its more than 180 adding or taking out 360 out of it to ensure always same side rotations. I will ask all further participants to send me their curves in advance so that I generate and check the robot code for cutting before they come.

I decide after this experience to ask all further participants for their curves when they come for robot training so that I make the locators and prepare the robot code for them. In this scenario when they come for the design task the files will be ready to run and they only have to focus on developing the design and the feedback. I will also tell participants that if they are super busy to create their curves, I can prepare a set for them and relax them so that they still do the design task.

10.11.16

Writing up day and fixing meetings with participants that have missed / change their dates. I do test runs of the code with both end effectors to be sure that things are running and spot further problems. The kinematic solver for the robot has a further problem where the 4^{th} Axis sometimes come positive and sometimes negative. A constraint is introduced to subtract 360 from it when it is over 0 to ensure that A4 is always at a constant -180 angle for the robot cutting exercise.

11.11.16

3 groups of participants come for their **robotic training session** (session 02)

Description of Session 02 for all participants:

All sessions of the day follow the same logistic, participants are invited inside the cage where the teach pendant is explained. This is the main communication device with the robot and typically used for online programming in factories and manufacturing plants. It is described how the robot moves can be recorded, manipulated and controlled from it. The buttons are explained emphasizing the dead man switch, the play button and the panic button. After these, the different jogging modes are explained and how the reference frames change depending which one is used. The axis mode is simple, for the base and tool mode participants are asked to look at the end effector which is positioned in a 35-degree angle and rotated upwards so that the difference can become obvious. Participants are invited to jog the robot after and test the different modes.

Once all of them have jogged the robot in its different modes 'targets' (bottles) are positioned on the table and participants are show how to record a program using the teach pendant. They are asked to reach the targets in any angle that they want. It is emphasized the fact that even if they have to make several moves to go from one to another the robot will not necessarily follow their moves as it will go in the straightest path and will only know about the recorded points, it will not know about the moves that happened between non-recorded positions. This is further illustrated by giving the example of an object being in between two of the targets and the user going around it when recording the path without recording those points but focusing only on recording the target. It is shown how the robot will knock down the object in between. The story of how in Brazil students tried to do a corkscrew like shape by recording, rotating around it and recording another point in a lower position is also told. Then they are asked what they believe the robot actually did.

After this each participant is invited to record a robot program and play it after in teaching mode. It is explained that teaching mode maximum speed corresponds to only 10% of the actual speed of the robot. Once all participants are done with this activity the group moves outside the cage, they are shown how to change the teach pendant to automatic mode and the safety measures for this. After, they each play their program in auto-mode.

11.00

The first group with participants CS2-017 (Jan) and CS2-027 (Alex) starts. The session starts with a discussion of their curves generation which are causing the software to crash. We check the problem and seems to be an issue with the graphics card on their computer and the latest version of Maya, it is suggested that they move to 2016.

After this we move inside the cage to start the training program.

CS2-017 (Jan): Will the robot know if there is an object that we want him to avoid? And how can he know this?

Alicia: That is a very good question, the robot in its current status won't know and you have to record points around the object you want to avoid so that the robot doesn't go through it. Even if you go around it while jogging the robot but don't record any points the robot will have no knowledge about it. There is no way for the robot to know about unrecorded movements.

To illustrate this further the researcher describes the case of students in Sao Paulo who wanted to cut a corkscrew looking shape by rotating a piece of foam attached by a gripper to the end effector of a robot and using a static hot wire cutter. Students recorded one point then twisted around A6 and moved the robot down to record a second point, the fact that not any points where recorded during the rotation caused the robot to cut a straight line rather than the expected path, the participant seems to understand this and be satisfied by the explanation.

CS2-017 (Jan): Can we put sensors into the robot to know that there is an object?

Alicia: Definitely that is an option and there is a lot of people working on integrating sensors to traditional industrial robotic arms, additionally there are also new versions of industrial robots that do include sensors. This robot in its current status cannot do that.

Participant CS2-017 (Jan) mentions how much fun the exercise is and that she wants to keep going working with the robot. She seems to get a good hand of jogging it and cleanly records a path. Meaning she moves from one point to the other by doing the coordinates in x, y and then adjusting the tool angle, after that moving in x and y using the tool coordinate system towards the new point rather than jogging around uncontrollably. By observing her behaviour, it can be deduced that a good understanding of the difference between programming the robot and running the program was achieved as well as a good understanding of the different types of jogging the robot and reference frames for each.

Participant CS2-027 (Alex) struggles a little with the different jogging modes and seems to be getting continuously confused between them. He tries to record a rather convoluted path avoiding the objects narrowly and moving between them but some points specially going up at an angle are not recorded causing the robot to knock out some of the objects when following the recorded path.

CS2-017 (Jan): How can we use robots in architecture and the construction industry.

Alicia: The researcher goes into a history trail, explaining the first attempts done by the Japanese to introduce robots into the construction industry to automate a lot of the tasks. She also explains how this failed due to the unpredictability and unknowns of construction sites, whereas purpose made factories are very precise and levelled for robots to successfully operate. This was followed by Gramazio & Kohler and their research in using robots for more creative tasks rather than just automating existing ones. The researcher explains that we are still in very early days but the addition of sensors which have become extremely small, cheap and powerful are adding robots to navigate and be aware of their environment and there is a good amount of research on how to introduce them to the construction site. The discussion continuous with examples of projects using robots in more creative ways and with novel materials more suited for robots such as the current pavilion at the V&A by the ICD and the material that we are going to use for this task.

We come out of the cage to test their paths in auto mode. Participant CS2-017 (Jan) jumps up to the sky the first time the robot does her path due to the speed so she misses the whole path which is then repeated for her to watch. The path of participant CS2-027 (Alex) is run without the ‘targets’ due to the different weird positions that the robot is taking and to the fact the he knocked them out during the test manual run. Both participants say they enjoyed a lot the day, they say the robot is very ‘cool’ and keep repeating that it was fun. Participant CS2-017 (Jan) has a lot of questions about the design task and how will it work with the robot so the task is explained to her emphasizing that it is about trying to design using the robot and getting information from him. Participants leave saying once more that the task was a lot of fun and they really enjoyed it and the robot as their giant toy.

13.00

During lunch time, unexpectedly participant CS2-018 (Bart) pops-up for some help with the simulation of his curves.

14.00

The second group of the day shows for robot training. This is formed of participants: CS2-010 (Kat), CS2-011 (Mar), CS2-020 (Soo) and CS2-022 (Pro). Three of them share their origin and they talk a lot on their native language. Participant CS2-020 (Soo) is from a different ethnic origin and keeps taking notes during the whole explanation. Participants CS2-010 (Kat), CS2-011 (Mar) and CS2-022 (Pro) who share the same nationality keep making jokes amongst themselves during the whole exercise. The training session progresses as described, participants never come as close to the robot as the previous group and seem less interested in doing complex paths, they all do very straight forward moves in reaching the targets and moving around them. Participant CS2-022 (Pro) remains the whole time standing between the table and the cage never approaching the robot, so he cannot really see the angle position of the end effector. During his path he keeps forgetting to record moves resulting in a highly unpredictable path as he doesn't know which positions are recorded and which are not, regardless of being the one that took the longest recording his path, his path is the more straight forward.

Participant CS2-020 (Soo) struggles with the teach pendant and with pressing the dead-man switch during the robot moves, but she ends up doing the most interesting path of this group, in terms of the rotations and angles in which the end effector is approaching the 'targets'

Participants CS2-010 (Kat) and CS2-011 (Mar) do very straight forward moves and don't seem to get overly involved with any particular aspect of the robot moves or path planning.

Participants leave after their paths are played in automatic mode, for this group each path is played two times as they get jump and joke during the first time missing a lot of them. They mention how much faster than expected the robot is in auto mode and also how they can feel the brakes and vibrations of the floor as the robot is moving.

16.00

The third group of the day arrives for their robot training session. The group is formed by participants CS2-023 (Har), CS2-024 (Ah) and CS2-025 (Efst). They are very good friends amongst themselves. They keep a having fun attitude and are interested in the limits of the robot: how far, how much, how fast can each axis move. They don't come near the robot but keep themselves around the table. This group doesn't care about the 'targets' on the table and is more interested in rotating the robot around the room. They ask about moving him all around the room and how far it can reach in each direction. Participant CS2-023 (Har)is the first one to record her path. She moves A1 all around the 360 degrees that it can so that the robot is moving up and down while going around the room, we all have to move further from the robot and closer to the cage as she is jogging it around but ends with a very dynamic path.

Second participant CS2-025 (Efst) is more interested in robot integration and how it can connect to other devices.

CS2-025 (Efst): Can you connect the robot to an Arduino?

Alicia: yes, but mostly to control an end effector working in his wrist not to control the robot moves as they are controlled and calculated by the controller. You can add an Arduino to use sensors that allow the robot to move according to sound, pressure, etc or to control the opening, closing, twisting, etc of an end effector.

CS2-025 (Efst): Can you do code to program different motions?

Alicia: yes, the robot can be programmed using offline programming where code is written for its different motions, however you cannot program motions that are not inside his working envelope (i.e. impossible positions)

CS2-025 (Efst): how do you program a new base?

Alicia: proceeds to explain this using the teach pendant and how it will change the X and Y moves of the robot.

CS2-024 (Ah): will the screws in the floor break if you program a new base?

Alicia: No, the robot cannot move from his position a new base will only change the reference frame of the robot altering his coordinates and the way he moves but not his physical position.

CS2-025 (Efst): Will it knock out something out if it's on its way?

Alicia: yes, unless you tell him it is there by programming moves around it, you could also integrate heat or distance sensors and program them as inputs so that the robot doesn't move near those objects. Additionally, a working envelope can be programmed if you are going to be too close to the robot so that it cannot reach you.

CS2-025 (Efst): Will it crash the table and go through it?

Alicia: most definitely yes, we need to be very careful in calculating the dimensions and distance of the end effector to avoid him doing that when we program it. The robot is not aware of anything else but himself so if you program him to go through the table or miscalculate the end effector's length, he will most likely crash it.

CS2-025 (Efst): Can you put wheels on it and have it moving around the room?

Alicia: Talk about the industrial robot on wheels developed by Gramazzio & Kohler which is full of sensors as it has to be calculating his position in the room continuously and also makes reference to other kinds of mobile robots which exist but are not industrial arms. The possibility of adding wheels and sensors to the robot so that it can navigate a room is discussed.

CS2-025 (Efst): If it had a bandsaw and you put it next to someone can you turn it off from the robot?

Alicia: explains the participant the digital inputs and outputs that the robot has which allow to control any tool at the end of its hand directly from the code.

The discussion continuous with participant CS2-025 (Efst) regarding integrating the robot to an Arduino for real-time control of the robot motions including object avoidance and collision detection. He records a path which is straighter forward and less adventurous around the room than the previous participant.

The last participant from this group CS2-024 (Ah) records his path. He gets a very good understanding and control of the robot moves with the teach pendant. He specially enjoys moving two axes at the same time which results in diagonal and circular moves, he keeps moving the robot in this kind of motions without recording the points. After jogging it for around 15 mins he records his paths which involves as the first participant moving the robot outside from the table area and facing the cage, from there he makes different moves that slowly take the robot back to the wall in front of the table. He jogs the robot for an extra 5 minutes after finishing recording his path.

We all leave the cage and run their programs in automatic mode. It is very interesting that this is the first group that although didn't get close to the robot tried to create more spatial moves and recorded paths outside of the constrained area of the table and the robot facing the wall in front. They mention it was fun and that they never expected to be able to actually jog the robot at will during the exercise. Their approach was very different and interesting in respect to other groups.

The group leaves asking me to design a set of curve paths for each of them for their design task as they don't have time to do them. With the aim of getting them more engaged in the task I ask what kind of curves or shape will each of them like? Participant CS2-025 (Efst) say some elongated looking shape. Participant CS2-024 (Ah) says something 'avocado' looking. Participant CS2-023 (Har) doesn't mind the shape and say whatever I want.

14.11.16

Robot introduction session for 4 more participants: CS2-013 (Nad), CS2-014 (Iv), CS2-016 (Mic) and CS2-028 (An)

I have to delay the session for these participants an hour due to problems with their trains.

17.00

Three participants arrive -CS2-013 (Nad), CS2-014 (Iv), CS2-016 (Mic)- the fourth one is running half hour late. We proceed with the session as with the other groups, these participants seem very comfortable in the robot space and throughout the explanation they are moving and walking around the table.

Participant CS2-013 (Nad) is the first one to jog the robot, she seems very comfortable with the robot very quickly and keeps moving the robot in the different modes, she doesn't want to give the teach pendant up. After 10 minutes I have to ask her to pass the pendant to the other participants so that they can also test and experiment with the robot. The participant says that she loves remote control toys and describes the robot as a huge remote-control toy. She managed to move the robot very smoothly without the continuous stopping and going from the other participants and without any hard breaking due to releasing the dead man switch or abrupt movements.

Participant CS2-028 (An) who came in late is quickly run through the different motion modes of the robot and the teach pendant is given to him to catch-up. He becomes enthusiastic about using two-axes at the same time while jogging the robot to get diagonal motions but he is not very smooth in doing that and runs into a lot of hard breaking from the robot. He starts the session by mentioning that he is a champion in the use of video games and hence remote controls and that he will master the robot but after a few moves he changes his discourse to say that he is very bad at and cannot control it as he wants, he seems to be struggling with the robot motions and not being very able to operate it.

CS2-013 (Nad): Will the robot know that there is a table of will he crash into it?

Participants are explained that the robot is not aware of anything else but his own body and will most definitely crash into the table if moved into it or asked to go there.

CS2-014 (Iv): Can the robot have sensors?

The integration and different kind of sensors that the robot can have is discussed.

CS2-028 (An): do you teach him IK or FK

The participant is reminded of the difference between both (from session 01) and explained that as we are teaching the robot the final positions it could be considered IK, the robot with its proprietary algorithms and integrated kinematic solver is figuring out all the rotations to reach the points that we thought it. Hence the differences between the points as thought and as performed and the unpredictability of robot arm moves.

CS2-014 (Iv): will it stop if it hits the table?

The participants again explained that the robot is aware of little else than itself and he doesn't know there is a table so most likely he won't stop.

Participants then proceed to record their own programs. Participant CS2-014 (Iv): keeps moving around the table and squatting checking robot positions when recording the program.

CS2-028 (An): does the Kinect work?

Alicia: Yes, the participant is explained how the Kinect works and how it is a crucial component of the design task as we are relying on a feedback loop that will allow him to compare digital and physical and be in control of the geometry through the robot manipulator.

CS2-013 (Nad) is very comfortable recording her program, moving around the robot and changing the robot positions by smoothly changing its moving modes.

Participant CS2-028 (An) moves around the robot to get the different positions, leaning and generally freely. He makes a very messy program as he doesn't record moves between 'targets' and goes back and forth sometimes recording and sometimes not which results in a situation where we don't know which are the recorded points and in which order they are recorded; the path is quite unpredictable. He seems the less confident and comfortable with the robot. This is weird as he started the session saying several times how good at gaming he is. He ends the session by constantly repeating how bad he is at this task and how scared he is of moving the robot and of his own program as he doesn't know where will the robot go. We play his program and it is slightly messy but the robot only knocks down one of the targets.

The group gets out of the cage to run the programs in auto mode. CS2-013 (Nad) jumps very high after pressing the play button and running her program in auto as she wasn't expecting this speed. All the programs are run twice except CS2-028 (An) who is still very afraid and uncomfortable although being assured that the robot will go to the exact same positions he went in manual mode when doing it in auto and won't break or move in any different way. He accepts for his program to be run once and is crossing fingers for nothing to happen.

All participants, except for CS2-028 (An), in this session seem very comfortable with the teach pendant and with the robot as from the beginning they were moving around the room and during the jogging and programming they kept moving around the table and generally kept themselves near the rig. They did have to be advised to keep some distance when someone else was moving the rig.

19.00

Online training session with Steven for atlas.ti coding and use. He guides me to the software and shows me how to set up a project properly and start coding it. The session is recorded for me to see later if I have any further questions.

15.11.16

9.00

I speak with Wassim about the problems running the scripts and robot code in the participant's machines and how I will change the workflow so that they submit their curves in advance and I will prepare all the code for them. They have already received the explanation of why putting the locators tangential to the curve is important and have seen a sample of how the code is prepared. If they want to know more, I will explain each step to them but won't stress them with this task. He agrees with this move.

I voice my concerns that some participants are too busy to prepare their curves or too stressed out with their design work and other commitments. I am offering to prepare a set of curves for them, while this can warranty that more participants complete the task, I am concerned on how will it affect their involvement and sense of ownership over the design. In setting out the experiment I thought that design ownership was crucial, so that when they are doing the feedback loop, they are aiming to achieve their initial designed shape. Wassim advises that I shouldn't leave them any homework of the work. The experiment should be completed while they are with me so that I can observe them, help them and take notes. He further suggests as a way to keep them involved to ask participants what kind of shape would they want or to draw me a sketch of the curves they have in mind.

I strengthen my decision to ask participants for their set of curves when they come for robot training so that I can prepare them in advance. I also start asking participants who ask me to develop their curves about what do they have in mind and what would the like to do.

18.00 (after DPM)

Fixing the robot code for 360-degree rotations on the 6th axis. Constraints are checked and modified to avoid these full rotations and allow for smooth cutting paths for participants. The code is tested and seems to work with a lot of different sets of curves but still it struggles on very specific points. The code keeps being refined and tested during the day by also changing the order in which the curves are given to the robot and the order in which the paths are defined to avoid the robot going around one after the other but rather doing side by side.

All the cutting paths are also moved from the centre towards one side of the table to avoid singularities and full rotations from A4 and A6.

2 participants last minute changed their meeting time and postponed for next week due to design studio work.

16.11.16

Morning code testing and end effector trials for the first participants to do the design task

15.00

A group of arrives for their robot training with participants CS2-009 (Vel), CS2-012 (Ele) and CS2-019 (Anas). Participant CS2-007 (Chen) generally training with this group is moved to another day due to design studio commitments

The participants describe the task like a lot of fun. After their introduction and jogging the robot participant CS2-012 (Ele) comments that she always saw the robot as something dead always in the same position but when it comes alive it is so much fun. She goes further to say that she really likes the way it moves as it is so 'elegant'

They proceed to record their program. Participant CS2-019 (Anas) is wearing a cast in one arm due to an accident and she doesn't have enough strength on the wrist to hold the dead man switch and the teach pendant. I ask her not to record a program if that will hurt her. She decides not to do it but sticks around chatting and watching the other do it.

Participant CS2-009 (Vel) obsessed with precision and getting the robot exactly in a straight angle to the centre of the bottle. She spends a lot of time aligning and realigning the end effector, she squats around the table but doesn't get very near to the rig. In her obsession to touch the objects exactly in the centre she knocks two of them down, although they are immediately repositioned when the program runs there is no way of knowing how precise it is as the objects moved

CS2-012 (Ele) is more adventurous and records a program mostly with the robot moving in the air, she goes outside the working space and makes the robot rotate in space and around itself.

Participant CS2-019 (Anas) although she doesn't record a program due to her pain, she is very comfortable moving the robot around and she does it smoothly with the teach pendant. As her design project is also exploring concrete, we discuss how concrete canvas is different from regular concrete and its potential for the design process. The conversation goes into the feedback loop during the forming phase of the concrete and before it starts to cure.

The group goes outside the cage where we play the programs in Auto and the participants are interested in other applications of the robot or how can they use it, we discuss the clay workshop I did in Barcelona and the foam cutting from Brazil. The discussion also goes into using the robot for updating vernacular construction methods such as the clay. They leave concluding that the session was a lot of fun. Participant CS2-009 (Vel) gives me her curves to prepare for the design task.

18.00

CS2-001 (Char) last participant for the day. He takes his robot introduction alone, and hands-in his curves before leaving. We spend time discussing more general aspects about the task such as the aim, the robot's role in the process and why are we using it, how does the material perform and what is expected from the robot and the human. He seems more interested in the overall overview and framing of the task than in the technical details. The participant starts to jog the robot, he changes modes and mentions that he is having fun and that he appreciates being part of something so fun. Initially he considers the tool mode to be the more intuitive from the 3 possible jogging modes but after moving the robot for more time he starts having troubles with the tool mode as it changes reference frame continuously so he left the tool mode and spends the rest of the task jogging between base mode and axis mode which he considers now more intuitive. He records an interesting path reaching the ‘targets’ in weird tool angles and moving outside of the table for extra points with the robot going around the room.

The participant seems generally interested in the task not only as a technical challenge but also its meaning and implications.

21.11.16

Meeting with participants CS2-027 (Alex) and CS2-017 (Jan) for their design task. Participants are feeling overwhelmed by the curve generation and simulation so we spend the time going through the digital workflow and I help them to generate their paths. Participants seem happy with their curves and resultant geometries which they hand over and we agree to reschedule their robot task for after their design reviews.

After they leave time is spent setting up and calibration of the Kinect definition in order to translate and align the Kinect origin with the rhino model and be able to accurately pass the information between both. This took some time but it all successfully worked at the end.

22.11.16

The day starts by fixing curves, locators and robot code for participant of the day CS2-002 (Nik). The export is working as well as the robot path. Heights have to be moved to 70 for cutting and 90 for the parts that are higher up for the robot to move in- between curves. The fixing of the rotations of A4 and A6 in the code is working but is also better for curves not to be continuous when selected so that they allow the robot to be moving around during the path rather than in a circular fashion.

IT lent me a card reader to move the information from the camera as the memory is full but this is not working, I have to find one alternative cable at home and order more memory sticks for the video just in case.

Meeting with CS2-003 (Val) who sent a very random set of curves that are not really up for the task as they have 90 degrees’ corners which the rotary blade won’t be able to do. We agree that I will change this for her to allow the robot and more importantly the blade to turn correctly in all corners. The way of fixing it without altering her design intent would be to remove the corners and allow the curves to slightly cross over each other when reaching the corner. She leaves and agrees to come later for the session.

CS2-002 (Nik) arrives, we test her path and it seems to be ready to go. We have to manually correct 3 rotations that are still causing major twists but it is only the coordinates of 5 points so we decide to do this manually. She helps me by subtracting 360 from the coordinate on A6. After fixing this the code is ready to go and the robot doesn’t do any more rotations on A6 while on the fabric.

I explain to her that after cutting she needs to hydrate the concrete as much as possible and mount into the frame so that we can proceed to the scanning and feedback part of the test. I help her to set plastics on the floor to protect during the hydration process. We prepare the frame, water bottles and staple the fabric to the table in order for the robot to cut it first.

We do a last test run and realised that the robot is skipping the lower part of the outer curve. I decide to quickly add more locators to the outer curve, export them and add them as a new path after the last one.

The cage is closed and robot running the cutting. The robot is almost done when it suddenly goes too low during the last path damaging the end effector against the table. The robot is stopped immediately; the blade doesn't brake but the wooden piece that holds the cutter detaches from the plate and the plastic parts of the circular cutter break, now the cutter swivels due to this broken bit and becomes unusable as its precision will be considerably less. Upon reflection I forgot to move the 'z' values of the last path done to 70 so they remained in their original 64. I explained this to the participant and apologise for having being uncareful and ruining her last run. I quickly order another blade in amazon and agree to meet on Thursday for a repeat. I feel very silly for having allowed this accident to happen by being careless and trying to create a path very quickly. I reassure her that all is good and the participant doesn't seem scared, she says that she is ok.

CS2-002 (Nik) leaves the room after a 2-hour session and I demount the end effector to rebuild it tomorrow. Rotary cutters are ordered from amazon and expected for delivery tomorrow.

CS2-002 (Nik): Was this a very fast speed and would he crash the table?

Alicia: No, the robot is actually moving at a medium- low speed otherwise the fabric will be ripped, he can crush the table but if he was moving at a faster speed and with lower points. In this case the speed was low enough to allow us to stop the robot without the plastic cutter being destroyed and without any damage to the blade

Alicia: Are you scared? I am very sorry that this happened when we were very close to move into the other stages of the task.

CS2-002 (Nik): No, not at all is just good to know the robot capabilities.

19.00

Participant CS2-007 (Chen) arrives for his introduction to the robot. We start by talking about his problems with the digital file and fixing them. His file is crashing continuously as he tries to split the mesh. After a few tries I asked him to leave it with me so that we can do the robot introduction and I will have it ready for him tomorrow. The file is not running in my machine either, there seems to be some problem with the history of his geometry causing Maya to crash, the curves have to be rebuilt and history deleted. There is no tool on the flange now so the explanation of the tool axis is slightly more confused and the differences have to be emphasised by rotating it more. He tries to be very precise and moves the robot around the new targets touching them and continuously changing between moving modes. Mentions that the axis mode is not very intuitive and he prefers the other two. Without tool the plate in the robot flange has to be touching so objects get knocked around easier. We then proceed to the explanation of how to record a program. Initially he seems comfortable and says that he understands it. When recording his program, he makes a lot of moves to avoid the object heights which are not recorded while changing modes to go from one to the other. We run the program and the robot knocks out both water bottles on his path, this makes the participant reflect on what was explained previously and conclude that if he moves the robot a little bit up to avoid and object this has to be recorded. I mention that this is important also when thinking digitally about sending code to the robot. After each curve we have to move the robot up as he goes to the next one otherwise the fabric, in this case, and any material he might be using in the future will break.

Adding extra points to allow for some movements to successfully occur is part of the way the machine thinks and is clearly not intuitive for participants in their first approach to the robot. They say they understand it but struggle to record all the needed points or more importantly to understand and think how will the robot move from one point to the other.

CS2-007 (Chen): So, if I only go a little bit up, I have to let the robot know because he only understands about points, right?

Alicia: yes, any move that is not recorded but only performed to avoid an object will be unknown to the robot and he will move in the optimal path between the recorded points, he is not aware of his environment or any other objects on it if you move him a little bit up after reaching a target in order to go to another one without recording the move he won't know.

CS2-007 (Chen): I see, I can understand now it is important to move him a little bit up after reaching a target and record that.

We go outside the cage to play his program in auto mode.

CS2-007 (Chen): that is so much cleaner than how I recorded it and so fast

Alicia: Shall we play it again (and proceeds to do it) yes, the robot will look for the best 'optimal' path between points and dismiss any mess or continuous change of mode that you might have been doing while recording them.

CS2-007 (Chen) says that he is very happy after the exercise and it was very good for him to understand how the robot moves as he want to use him to build a model of his studio project. The discussion then moves into parametric modes of incorporating/merging robots with vernacular architecture which is a topic of his interest and that he is writing an essay on. Conversation keeps going with the researcher providing examples of robots using traditional materials but adding something new through innovative geometries, or the way they manipulate the material such as the brick winery by Gramazzio and Kohler and slip forming casting by Lloret et al. The researcher also discusses the work she did in Barcelona spraying clay with the robot and provides references to the vernacular Moroccan earth architecture that were used during that exercise. The participant leaves after taking notes of the projects above mentioned and shows interest in learning how to control the robot path through grasshopper which is agreed to be thought later to him.

23.11.16

The 45mm olfa rotary cutter for next day delivery is lacking a perforation in the middle to secure it to the wooden post, the cutter model is slightly different, hence when attached it moves to the sides and cannot be used.

The day is spent preparing 'avocado' looking curves for CS2-004 (Epa) and testing them in the robot to find a new correct height that will fit all of them and also work for the other participants as per the problem yesterday with the heights. The table is also not straight meaning paths closer to the wall don't get cut at a height of 70.02 but at that same height if the paths are closer to the robot he will crash into the table. The positioning of the paths for cutting and their corresponding height is tested to avoid more disasters similar to yesterday's.

Dan is not in the workshop today and Carole (the services manager) has to leave early so when I arrive at 12.30 to fix the end effector they kick me out and I don't have replacement for the angles to the sides of the end effector wood holder that got twisted yesterday after the impact between the robot and the table.

14.00

Participant CS2-004 (Epa) arrives, I explain him the situation with the end effector and he happens to have some angles that he used to create a box to ship a model. He allows me to take 2 out from his box, using the robotic automatic drill I unscrew them. I try to fix the broken knife in the robot lab using the screw driver. The cover of the knife is out as it cannot be put down anymore due to the plastic pieces being stuck. While screwing it, the end effector rotates slightly cutting the edge of my fingers. I place a band and keep working. We try to fix the end effector with the available tools and using duct tape on the plastic pieces to keep them from moving. This is not very successful as the knife still swivels to the sides under the robot pressure. If the cuts are to be done this way there will be a high degree of imprecisions on them. I explain this to the participant who initially is keen on getting them done anyway, so we do another air run but the knife is moving a lot and some cuts are not performed due to it being in a slight angle rather than straight. I tell the participant it will be a lot better if he can wait for the new knife to arrive, which should happen tomorrow, before we do the exercise otherwise, we won't be getting anything useful out of it. He agrees after one more air run and is agreed that he will come tomorrow when everything is in place.

24.11.16

The new knife arrives on time at 1.00 pm for it to be positioned, the end effector gets properly redone using new angles and calibrating it to ensure is fully vertical with the new blade. Participants are now expected to start arriving for their design tasks. All technical and physical problems so far seem to be finally sorted out. The dynamic as explained to each participant upon arrival is designed and to be done follows: (Session 03 – design exercise – full explanation)

1. Participants code for cutting and robot paths have been tested in advance by the researcher and is loaded into the controller. They arrive and cut their piece of concrete canvas, if I haven't been able to do it for them. This will be a case by case situation depending on the number of participants. While they do that, the researcher gets the water on the bottles, and loads the obj mesh of their relaxed mesh into the rhino model. The mesh will be positioned in the digital frame located in the same corner of the table as the real one will later be. It is rotated by 180 degrees as the simulations were done with the gravity going up whereas the robot actions will be of pushing.
2. We do an air-run of their cutting paths in auto mode to see exactly where the path is located. After this the participants go inside the cage and staple their concrete canvas on the area where the robot will cut it. We come out of the cage and the cutting path is run.

3. Once the robot is done cutting, we go inside the cage I will change the end effector from the knife to the Kinect scanner, during that time they will hydrate their fabric as much as possible using both water bottles and throwing the water at it in case the spraying is not enough until it is fully soaked. The Kinect end effector has to be mounted with the robot A4 at 0, A5 at -60 and A6 at 0 for correct translations and rotations in relation to the digital model.
4. The piece will then be stapled to the provided frame. The frame will then be positioned in the designated place on the table, this is to be sure that the digital and the physical models are on the same location.
5. The robot will be positioned for scanning, they get a short explanation of the minimal distance that the Kinect needs in order to get a successful point cloud. Participants will manually move the robot to choose where to scan from. The computer will be running a processing script (prepared for them) that allows them also to remove background and scan only the parts they need. By pressing the key ‘r’ a text file of the point cloud is recorded. This is in order to know the starting position of the cloth in relation to the expected final deformation.
6. The text file is then imported into rhino and loaded to a grasshopper definition. Participants have to input the cloud into the definition as well as the x, y, z positions of the end effector (taken from the teach pendant). The definition will then use the coordinates of where the robot is located to translate the centre of the point cloud. The point cloud will then be translated and rotated into rhino space and finally rotated and translated to the same place of the table where the digital model is. This process takes like 30 seconds as everything is automated. Participants only need to input their point cloud (taken from processing) and the position of the end effector in cm (taken from the teach pendant). They then go to the component which shows them the point cloud in relation to their digital prediction.
7. After using the ‘translating’ definition participants further reduce the number of points by using a range component this in order to get rid of extra points corresponding to the frame or other elements that might be still be around. The resultant point cloud is then compared to the digital prediction. Points from the scan that are still above the digital simulation are isolated and their coordinates sent to the robot platform to generate further robot pushing code.
8. Robot code is generated for pushing in the specific locations and sent directly to the robot. The computer and the robot share an Ethernet connection making the code transfer direct.
9. Participants run the robot either in manual or in automatic mode, depending of their own preferences and design idea. The ‘pushing’ code, includes a rotation of A6 around each point to ‘massage’ the material and increase its deformation. Participants are encouraged to hydrate the material during the rotation of the sphere. They can also do further pushing by operating the robot manually outside of the generated code. The researcher, or the other participants in the room would be helping them hydrating the material while they do the manual iterations.
10. Steps 5 – 9 are repeated until the participant is satisfied with the resultant geometry. Finally, the concrete gets around of spraying to ensure that is fully wet and is left to settle.

14.00

CS2-003 (Val) arrives for her design exercise. I ask her to cut a piece of the concrete while I get some water. We do an air-run to find the exact location of where the path is and proceed to staple the concrete fabric in that approximate location. After the cutting run some of her curves specially toward the upper part of the table are not fully done (the robot only went halfway through the fabric) I ask her to pass a knife on them and proceed with the hydrating while I change end effectors. Some of the over crossing in her paths have caused the fabric to fully disconnect for some of the corners so it hangs.

The first scan is done and due to the ripped parts, there are hanging part very much lower than what was expected digitally. The participant refuses the idea of the robot doing the pushing as she prefers to do it manually herself. I show her the definitions and the points where the robot will push (in the screen) where her fabric hasn't deformed as expected. The participant still says she prefers to push those points jogging the robot manually and proceeds to do it.

The participant starts pushing and by pressing the robot too much against the fabric she causes weird deformations of the material as it goes very low. She says she likes this better than her previously designed and simulated shapes and pushes the material even lower from the centre by moving the sphere at the robot end as low as possible before breaking it. She says she is having fun and is not very concerned about the final shape being similar to her simulated one. We do another scan which shows that the physical model is a lot lower and much more deformed from what was expected. The participant dismisses this information saying that she is happier with how it is looking after extreme pushing, almost ripping it, and doesn't care anymore for the digital model. The participant keeps pushing and massaging by jogging the robot refusing any further scans or relation to the digital model.

The fabric has certain springiness so that after the robot pushes it tries to come back to its original shape. The participant asks if she can leave the robot with its full force pushing in the centre as in this way she can make the material go lower and leave it like that until it dries. She asks if she can come next week to fix some of the hanging bits due to the ends that broke during cutting or do another iteration of her design now that she saw how will it work out.

She mentions that the robot helps her be faster and more precise but is not like another human as it is not giving her any opinion (she is not asking for it) and she is only following her intuition. The participant keeps pushing and massaging until she is happy, we add more water to the shape. We then proceed to the interview and the questionnaire. The participant leaves after completing the exercise. She only performs two scans and does a lot of pushing and massaging always jogging the robot manually. She describes her experience as fun. The exercise takes around 2 hours, 2 scans and CS2-003 (Val)didn't considered any of the feedback offered by the robot in the actions after the scanning step.

16.30

The second participant – who came yesterday when the end effector was not working CS2-004 (Epa) arrives for his design exercise. He is a more hands-on person and from the beginning he wants to mount the end effector and move the robot with the teach pendant himself into position for doing the change of end effectors (the robot joints need to be at: A4 0, A5 - 60, A6 0 to ensure that the end effector is in the correct orientation. He doesn't need to cut a piece of fabric concrete as his piece from yesterday remains waiting for him. We run his cutting file and proceed to change end effector, hydrate and get ready for pushing. This participant asked for the design of 'avocado' looking curves so I show him the simulation and expected shape from the set.

This participant, similar to the previous one, doesn't want the robot to do the pushing using the generated code but he wants to manipulate the teach pendant during the pushing process. We take an initial scan of the shape before any manipulation is done and compare it to the digital prediction. The participant is a perfectionist in trying to push on the areas or points that the computer is showing, and were the robot would have gone, but doing it by himself. He takes on-board the suggestion about rotating A6 and is massaging the geometry all along as well as pushing. The computer is showing that points in the left area and centre require further pushing and he concentrates his efforts there. The participant seems very engaged with the design result although he is not fully happy about it. He keeps pushing in different areas to make it look differently.

We take another scan which doesn't show a lot of deformation comparatively to the initial condition, as he has been pushing in the central area it seems that the sides have sprung back to counter effect this force. This participant is not as aggressive in using the robot for pushing by moving it very low, he is more concerned with massaging and going all along up and down the geometry. He doesn't want to do any further scans of the result and says to be mildly satisfied with the result as the geometry is not deforming as he expected.

After 3 more rounds of pushing he asks to place a brick on top of the thicker area so that the material doesn't spring back and increase deformation. The researchers agree and he places a brick and hydrates the shape. After this he considers his design to be finished, he is not fully convinced whereas he likes it.

We proceed to the interview and the questionnaire; the participant asks if he can come tomorrow to see how the shape looks once it dries. The second complete design task is finished. 2 scans total, manual pushing iterations although consulting with the computer the areas where the shape was not deforming as expected.

After CS2-004 (Epa) leaves I stay fixing the code to make the feedback faster and modifying the orientation of the Kinect end effector as it was going into the material at an angle. This was done initially on-purpose, the angle of the Kinect end effector is controlled by an attractor point that participants could move around the grasshopper definition on top of the mesh. The rationale behind was that in some cases pushing at an angle could be attractive and a way of using the rotational capacities of the robot. After observing them, it seems they prefer to push straight down so the definition is changed to only push straight.

25.11.16

Early morning: fixing curves and robot paths for CS2-005 (Sim), CS2-018 (Bart) and CS2-026 (Gian) who will come in the morning. CS2-018 (Bart) and CS2-026 (Gian) provided their curves, CS2-005 (Sim) asked for a design to be made for her. CS2-018 (Bart) is particularly engaged in the digital workflow and provides not only the curves but also the simulation of the final relaxed shape. CS2-026 (Gian) is very keen on having a shape where half goes up and half goes down. He doesn't have a simulation achieving this effect in his simulation both halves go down but expresses this as his design intention.

12.00

CS2-005 (Sim), CS2-018 (Bart) and CS2-026 (Gian) arrive and I ask them to cut their pieces of cloth while the setup is finalised. For CS2-005 (Sim) exercise I want to test a further iteration of CS2-003 (Val) curves. Trying to shorten the cutting distances so that the curves don't rip in the corners and making it to cover the full size of the frame. The design that CS2-003 (Val) did is a perfect square whereas the frames are rectangles so she only attached the corners making the deformations less accurate. For CS2-005 (Sim) the aim is to fully constraint all edges and only pop-up the centre making it more like a wall panel and not like a shell.

The robot cuts all of the 3 patterns. CS2-005 (Sim) still gets some tearing at the edges. It is confusing why is that happening as lines are now further apart at the corners. Before hydrating participants have to do a final pass on the cuts that are higher up on the sheet as the robot didn't go all the way through on those ones. This is due to the slight angle in the robot mount which makes him still being a bit higher on the top end of the table (closer to the wall). This was fixed for the previous participant but happened again in these set of cuts.

After the end effector is changed and participants have mounted and hydrated their shapes they are asked if we should start the first pass of robot pushing.

CS2-005 (Sim) is the first one to scan how the cloth is hanging and when compared with the digital simulation the overall shape is shallower than expected but the areas that tear down are hanging lower than expected. I show her on the screen the points where the robot will push in order to make the overall shape go lower and hence more similar to the digital shape. The participant looks surprised that the robot can do that and initially agrees to send the code for pushing. CS2-005 (Sim) changes her mind one minute later as she is concerned that the robot will further tear the fabric. I assure her that the robot will only push and massage the areas that are coloured in red (the point cloud comparison displays a gradient colour) where there are differences. I also show her the grasshopper green points which mark exactly where the robot will go. The participant decides that she prefers to jog the robot manually regardless. As she pushes some of the fabric tears further so when the second scan is performed and the initial and current status compared the tears are hanging much lower, although the overall shape has been much more deformed than what the digital simulation anticipated. The participant is offered again to use the robot path to push rather than manual jogging but she thinks that if she does it that way she won't accomplish her desired shape so she prefers to jog the robot while pushing and massaging for an extra session. She doesn't want to take a final scan as she says she is happy with the obtained shape. 2 scans total, consulting the feedback but ignoring any information provided by the robot.

CS2-018 (Bart) is the next one. He is more interested in the feedback from the Kinect and the scanning than the previous participant and wants to perform the first scan to see how the shape looks in comparison to his simulation. He is also very much in love with the shape he designed. The participant performs an initial scan and decides he wants to push and massage manually jogging the robot. We do another scan which shows areas of the geometry higher than what was expected from the digital simulation. He agrees to send the code for the robot and then manually run the pushing program. After a successful push the robot pushes a bit hard on an area that was already very fragile (just connected by a few threads to the rest of the shape as the joint was too small to stand the kick of the cutter i.e. when the knife goes out of the material it doesn't do it straight but does a bit of an angle which results in a slightly reduced joint area from the one initially sent) the area disconnects from the rest of causing one end to hang lower. The participant is clearly disappointed and says that the robot messed up his shape which he doesn't like anymore. I encourage him to push the other side by manually jogging the robot he does it for a little bit but keeps repeating he doesn't like the shape anymore. He is offered to do a final scan and is interested in doing it although he insists that he doesn't like the shape now. He is very disappointed and sad that the shape broke but is more enthusiastic than previous participants about the feedback from the Kinect. 3 scans total

CS2-026 (Gian) is the last one, he asks how can he achieve one half of the geometry to go low and the other one to go high. He suggests that the robot pushes once and then he flips the frame but due to the setup this is not possible to do as the fabric is stapled to one face of the frame, if you were to flip it the popped-up fabric will crash against the table and get flattened again. He doesn't want to do an initial scan as he prefers to deform the shape following his design intuition. Anyway, he explains the simulated shape is not doing what he wants to achieve. He does one pass of pushing and massaging manually jogging the robot and dismisses again any feedback as he doesn't consider it necessary to achieve his shape. After a few more passes of him jogging the robot to deform one side of the fabric (the one he wants to get lower) he places a brick holding on it to hold it further down. He then gets a piece of cork that was lying down in the robot room and places it against the frame to hold the opposite side of his geometry up. He decides that is enough, hydrates the fabric further making sure that the brick and the stick are on the places he wants and decided to leave it to settle, he doesn't want to perform a final scan on it as doesn't see any purpose for doing that. This participant had a very defined design idea from the beginning and he was strictly focused on achieving it rather than looking at what the material or the machine were doing, which he completely dismissed. 0 scans total

We move outside the cage to chat about their experience. CS2-026 (Gian) and CS2-005 (Sim) mention that for them the design strategy was an additional challenge to the robot task as they usually design what they will get whereas here they were not sure what the result would be when they were designing the curves. We do the interview (recorded), they answer the questionnaire and the 3 of them mention that they had fun with the task, specifically CS2-026 (Gian) who says he really enjoyed it (although he didn't do any use of the feedback)

16.00

S2-023 (Har), CS2-024 (Ah) and CS2-025 (Efst) arrive for their session 03. The 3 of them asked for paths to be made for them, CS2-024 (Ah) asked for an avocado looking shape, CS2-025 (Efst) wants a more elongated looking thing and S2-023 (Har) doesn't care.

For CS2-024 (Ah) I decide to do the same avocado curves as for CS2-004 (Epa) but now inside a rectangular border so that it can be fully attached to the frame, this also means that the outer edge is no more a continuous curve, and it needs to be divided so that it has cuts and joints that can also pop-up.

CS2-025 (Efst) asked for the elongated shape. I give him the same shape as designed by CS2-026 (Gian) but I adjust the simulation parameters so that it hangs lower. Also, this participant is not aware of CS2-026 (Gian) idea of one side going down and one going up, so the final result will be considerably different.

For S2-023 (Har), I fix the same pattern used by CS2-005 (Sim) (cuts are straight going in offset rectangles toward the centre) making the curves shorter on both sides of the corners so that they are further apart with the aim of preventing the tearing as has happened in both previous cases of this pattern.

All 3 patterns are moved towards the lower end of the table, almost aligned with the lower edge (near the robot) to ensure that they get fully cut and avoid participants having to retouch the higher ends of their patterns.

We do the air-runs for all of them as the position in the table has now changed to check where is best to locate the material. During the air-run the blade breaks while doing the avocado looking shape twice. I move the shape up by 0.5mm to avoid more blade breaking once the concrete is in place and makes more friction. We position the fabric and start to run the cutting programs. There is a shower of blade breaking during the avocado cutting. Regardless the fact that the whole pattern is now higher than any of the previous cuts the blade breaks 6 times. For each time the blade breaks we have to stop the program, open the cage and change it. This is surprising as the robot has cut this pattern before without any problem and also the whole file got moved up after the initial run. I will investigate this matter later.

The pattern of CS2-025 (Efst) is successfully cut without any blade incidents.

The square pattern is worse than in the two-previous iterations of this same pattern. This is very much a surprise as all the curves have been reduced in length so joint areas are expected to be larger hence less crossing but somehow, they result in more crossing, the result looks almost like shreds. I apologise to the participant as this is totally unexpected I spent a good amount of time fixing the pattern and offer her to cut any other of the existing patterns for her. She is inclined for the avocado but is worried about the amount of blade breaking so decides to go for the previous iteration of the rectangle- CS2-003 (Val)- I am worried as this one was more shredded. The version I prepared for her was supposedly fixed. We run CS2-003 (Val) version and it still results in a lot of shredding but slightly less than the pattern run first.

I explain to S2-023 (Har) what is going on and how that file was the first iteration which resulted in some shredding, got then modified to be the size of the rectangle and distance between cuts increased, as there was still shredding. I then reduced the distance between cuts even further on her version but somehow it only worsened the problem. I think is related to the kick of the circular blade when doing straight cuts that gets increased, also as the cuts got moved towards the lower end of the table this means that the blade is going deeper into the material so perhaps as it gets more depth it gets more friction and when it comes out the 'kick' is higher or the amount it angles, hence reducing further the expected size of the joints. The participant is ok with using this pattern regardless being offered another one.

S2-023 (Har) is the first one to work on her deformation. She makes an initial scan but also opts out of sending the pushing through robot code and decides to jog the robot manually to push and massage. Participants are shown that sending the pushing code is a rather fast process as we only compare points clouds, get a text file with the coordinates of the points that are further, generate the robot code and copy this into the robot controller.

In general, all participants so far are happy using the processing script for scanning, the cloud translate script to get their scanned point clouds in the same position where the digitally simulated is, they show surprise after inputting the coordinates of the robot end effector and seeing the point cloud on top of their Maya mesh. They also enjoy seeing their point cloud colour coded based on distance to original mesh. But even with this all of them have selected to push and massage by manually jogging the robot.

Participant S2-023 (Har) does 3 scans and compares initial status of material with expected, intermediate status after deformation and final status. Because of the tearing the digital model is of no use to compare as it is way off from the physical reality but the comparison between the different states of the physical model after each iteration of pushing and massaging is very interesting for the participant and she mentions how seeing it on the screen makes more obvious the material deformations. 3 scans total

CS2-025 (Efst) is the next one. He asks about point clouds and how they work, how are they different from only a set of points and how are they manipulated inside grasshopper, we have a long conversation about all of these differences. I show him that a set of points cannot be loaded as a point cloud and a point cloud has to be decomposed to remove information from it before it being loaded as a group of points. The other two participants are chatting outside the cage as the discussion goes for over 15 minutes, the participant is very interested in manipulating point clouds, what information they convey and how do the computer read and utilizes them. He is also interested in the series of translations and rotations that are being done in order to move the point cloud from the Kinect origin to rhino space and finally to the model space. The conversation is very interesting as the participant seems to be very interested in the digital workflow and how it works rather than only on the technicalities of the task.

This participant also makes 3 scans, after the first scan is obvious that the physical model is hanging way more than what the digital model predicted so the comparison with the digital model is not really working, also because the robot is looking for points where more pushing is needed and not for points that need to be higher up, the robot cannot pull anyway. But the comparison between the different states of the geometry is very interesting as the material gets pushed by the participants. After the participant pushes it seems as if the fabric is bouncing back to a previous state without much happening but the scanning shows that a lot of deformation is actually going on. This participant spent a good amount of time massaging the fabric by rotating A6 at each point he wanted lower. 3 scans total

CS2-024 (Ah) is the last one, his shape – avocado- looks generally very nice. He also decides to jog the robot for pushing and massaging but does 3 scans throughout the process. This participant also spends a good amount of time 'massaging' the fabric by rotating A6.3 scans total

The 3 participants on this batch did 3 scans while deforming their shape comparing between initial condition, condition after pushing and final condition. They didn't want the robot to push with an automatic program but differently to previous participants they kept comparing how it was deforming in different states of their pushing. The robot as said before cannot push upwards and in all their cases the digital simulation was shallower than the physical models so the set of points being sent to the robot was not really working as it only looks for lower points. The point cloud comparison and translation were very interesting for them. They mention that the continuous scanning helped them understand how the material was deforming.

These students are from a year higher than all the previous ones that have done the exercise so far. Although only one-year difference they have a more mature approach and are considerably more interested in the feedback. They say it is the best part of the process, whereas younger participants totally dismiss it in some cases.

This group spent almost 4 hours on the task, a very large amount of time. The blades are definitely not suited for straight cuts and simulations, in their case, are too shallow. The fabric here is deforming a lot more than what it did in previous exercises. I will look into its parameters. Finish after 10pm

Observations after working with this group: one pattern was a disaster (no curved one) other two cut and deformed very well. Due to the fabric and circular blade potentially, straight cuts won't generally work as there is an extra 'kick' from the end effector at the entry and exit points. A lot of blades broke but patterns get cut better on the lower end of the table. Conversations were more interesting as well as their approach to scanning and feedback. Simulations are very much off and parameters have to be amended.

The comparison between the different states of pushing is very interesting and participants are describing it as providing them insights into how the material deforms, which they feel they don't get while doing the task as they are immersed in their design process. They describe that the real deformations are shown on screen are different from how they are perceiving that the material is deforming in a lot of areas. VIP: I should develop a definition to compare the different point clouds taken at different stages of the process rather than only the digital simulated mesh and a point cloud as this seems to be providing more insights to the participants about their process.

30.11.16

Early morning fixing curves and paths for participant of the day. I also adjust the parameters for his simulation based on observations from previous participants were the expected digital shape is a lot less deformed than the resultant one.

Smoothing the code for the plunging so that participants feel comfortable that the robot won't push more than expected and rotations around A6 while massaging are smoother.

18.00

CS2-001 (Char) arrives for the design exercise. We start with a conversation about the different stages of the process and the tasks that the robot will perform. The tasks that I will perform and the tasks that he has to do. The robot cuts his path which was tested in advance and the blade breaks in one of the outer curves, during testing there was a blade breakage when it was doing one of the sharpers inside curves but not with the outside one. I fixed the interior one prior to his arrival but wasn't expecting the blade to break on the exterior one. We change the blade and finish the cutting. The participant proceeds to hydrate his fabric while I change the end effector and refill the water supply.

I encourage him to use the robot for pushing but he insists in doing it by himself. The fabric has an initial deformation larger than expected. The 'horns' hang out almost immediately but not the central part. The participant takes an initial scan of the status of the material before starting to deform it. I give him the option to rotate A6 while on the material to 'massage' it and make it go lower. After a first iteration of deforming by pushing and massaging, the participant scans and is surprised to see how much the material has deformed from his initial shape.   The participant says that he likes the grasshopper definition translating point clouds and describes it as cool. He asks if he can try to deform again as he wants to push the central area to get the horns to move up as a counter effect. Participant pushes and massages again. During the massaging he presses a bit too hard, or loses control of the Z-axis causing the fabric to break loose from the frame 2 times. I help him by stapling it again and watering it continuously. Participant takes another scan which shows one of the horns higher than the initial position but the centre and the remaining horn is way lower (screenshots from rhino) It is difficult to know if this is due to the behaviour of the material or to the stapling when the fabric fall. He goes for a final round of deformations

The participant asks if after learning directly from the material it would be possible to have another go at the design and change some of the parameters that now he understands. The researcher tells him that absolutely, that will be an ideal situation. I also mention that maybe the explanation I did about how thicker and thinner cuts influence the final shape was not clear but he assures me that is due to not being able to visualise the behaviour of the material until he sees it. I encourage him to do another iteration of his design.

CS2-001 (Char) does another round of pushing and massaging as he wants to push the sides where he left thicker sections of material. After this he performs another scan and now the deformation is clear, one of the horns has maintained a very similar position since the first round of deformations but the other horn and the centre have been pushed down considerably. Between the second and the third scan the central part came up but, more likely, this is due to him pushing the sides causing the centre to come up as counter effect. Between the third and fourth scan there is more coherence in the deformations of the horns, the same can be seen between the first and second. Differences between the second and third scan are not very understandable as the horns look down but the centre is up. An explanation for this can be the re-stapling, hence the position of the piece being slightly different altogether or to him doing a lot of the pushing on the peripheral area. This participant does 5 scans, which is more than any other participant has done so far and is continuously asking to see them in different colours before doing the pushing. It seems that they are informing his further design decisions.   5 scans total

During the interview, he mentions that the feedback from the robot allows him to have a clearer understanding of what is going on and how the material is being affected, he thinks that without it because he is so immersed in the process of creation he was thinking that the horns were deforming a lot but when analysing the scan, it became clear that they maintain a more regular position than the rest of the shape. For him the deformations of the material as seeing by the designer are a lot more subjective and mixed between what he believes is happening and what is going on as he doesn't have an overall perspective. The robot helps him to have a more objective view of what is going on and be clearer about where are the deformations happening. (this can be heard on the interview)

Observations: It is becoming evident from the participants so far that as they get older, they rely more on the feedback or at least use it more/ influences more their thinking. 2nd year participants so far have scanned once, third year 2 or 3 times, postgrad participants 4 times. This might be due to younger participants being more about having fun with the robot or more keen on just following their intuition to deform whereas more experienced participants are interested in knowing and understanding what is happening to the material or how it is deforming before doing more moves? Additionally, older participants are asking if they can redo the design now that they experienced how the material performs. Based on observations so far it would be recommended not to introduce robotic arms until 3rd year to architecture students. Observations recorded with the previous group are confirmed in terms that although the participant refuses the pushing to be done by a pre-generated script and wants to jog the robot during the process the participant wants to be scanning continuously and expresses that looking at the different point clouds gives him insights into what is happening to the material that differ to what he perceived or thought was happening only by looking at it. It allows him to have a more quantitative idea and make decisions based on information that he wouldn't have without the Kinect or the scanning.

VIT: work on definition to compare point clouds.

Simulations present a lot of variation, further tweaking to the parameters is needed.

After finishing the interview with a lot of insights the participant answers the questionnaire and we have a conversation about how to exhibit the different pieces that are being created by the different participants before he leaves.

02.12.16

8.00

Arrive to unit to test the robot paths for the participants of the day. The group that is coming in the afternoon asked for shapes to be generated for them so I have to finish them, relax for digital model and generate robot path.

CS2-006 (Jac) is the first one scheduled for today. He already had 3 sessions. During his third session he tried to export the locators and generate the robot path, he is generally very interested in the digital workflow, but the robot was doing to many 360 degrees rotations in A6 (it wasn't fixed). After fixing this, he had a lot of 'ghost' locators being generated on his computer -as previously described-. The code and geometry were generally not working and after a 3-hour long session he left and we re-schedule for today. He left me the file with the exported locators but I asked him for the Maya curves and he sent that file by the 29.11. In preparation for his session I exported the curves but rather than sequentially to avoid the robot going on a circular motion, I exported them by sides, the shape is a diamond, so all curves on one quadrant are first, then the next quadrant, etc. Previously they were exported sequentially for each radial offset, meaning the robot had to go through all 4 quadrants of the shape in each curve and I speculate that is what resulted in so many A6 rotations plus the code didn't have any constraint to fix this. I prepare his robot path and test it early in the morning, it seems to be working perfectly!

12.00

CS2-006 (Jac)arrives for his fourth session. We speak about his path and I explain to him how it got fixed and also the advantage of selecting the curves in order by quadrant rather than sequentially around the curve. He cuts his piece of fabric, positions on the table and we proceed to run his cutting path. After this he hydrates the fabric and hangs while I change the end effector and load his digital simulation in the computer. He is happy and interested in scanning. We scan the initial shape after hanging and the robot gives 200 points where he finds differences and proposes to push. The participant is excited and decides for the total automatic pushing but the code is run on teaching mode. He holds the pendant while running the code (around 400 lines as per each point there is a rotation on A6 and then the robot goes up to move to the next point.) After running the code, we do a second scan and the robot gives 111 points where there are differences and proposes the push, the participant decides to run the pushing code again as proposed by the robot but he is holding the teach pendant and running the pushing code in teaching mode. The code is being copied through Ethernet to the robot so is very fast to change. After the pushing is done he decides he wants to push a bit more in certain areas by manually jogging the robot before scanning. During his third pushing iteration the fabric rips slightly on a joint that was weak from the cutting stage. The participant keeps jogging the robot manually to push in different areas. 30 mins of pushing and he decides that the is happy with the result. The participant doesn't want to scan again, he thinks that now the physical shape will be very different from the digital model as the fabric slightly rip in one part. He asks for the grasshopper definitions that take the point cloud from the Kinect and translate and rotate it into rhino space first, then compare with digital model and finally generate the robot code based on the points that are above the digital simulation within a predefined range. We move to the interview; he says that he enjoyed the feedback and getting information from the robot. Participant answers questionnaire and leaves, the process took around 2.5 hours. The participant did 2 scans and ran 2 robot pushing programs with a last iteration of manual jogging for pushing.

I feel very happy with the new parameters of the concrete canvas digital simulation as it is less stiff and relaxes more which allows the robot to propose pushing points after the initial scan. Now, after pushing the digital simulation are looking very close to the physical results. The new parameters are working great!

15.00

CS2-002 (Nik) shows up for the design task without notice (she send me an email two hours before when I was with the previous participant saying that she was coming, so her cutting path wasn't double checked) We try to run her path and the robot seems to be going lower when it is cutting the edge curve, there is also one full rotation on A6 towards the end of the path which can rip the fabric, we fix the rotation and check the z-value for all the points in the path. We run the path again, there are still 2 full A-6 rotations and there is something weird going on with the z-values as in the path.txt file all are at 70 but when cutting the robot goes slightly lower. I tell the participant that due to her extremely short notice and that I was busy the path was not checked and we agree to reschedule for Monday as I prefer to use this time to test and check all the paths of the participants that are scheduled for later this afternoon.

17.00

CS2-013 (Nad), CS2-014 (Iv), CS2-016 (Mic) and CS2-028 (An) show up for their session. These participants asked for a design to be made for them. I showed them the four designs with the sets of curves and resultant digital simulation and assign one to each. CS2-028 (An) gets the 'cycle seat' (elongated and 1D scaled version of avocado), CS2-013 (Nad) the diamond (CS2-006 (Jac) shape but scaled and inside a rectangle), CS2-016 (Mic) a modified version of CS2-001 (Char) shell inside a rectangle and CS2-014 (Iv) an elongated designed shape for him.

Participants cut their fabric and we start to run the paths. They mention how difficult it is to cut the material. The first path to be cut is for CS2-013 (Nad). Blades start to break one after the other without a significant reason, especially as this is a modified version of the same path that was cut this morning, the robot has to be stopped continuously and the key passed around to change the blades. The participants get worried as blades are breaking every 2 minutes and the situation is becoming desperate, but they remain calm. I explain to them that these number of blades, one every 2 minutes, hasn't happened before and that it is highly unexpected as this same path with some slight changes was cut in the morning. They suggest that a reason could be the amount of concrete that has been accumulated in the table as the previous participants hydrate and hang their shell in the same corner where the cutting takes place. They suggest to scrap the table and we do with the screwdrivers and some pieces of wood available. The blades are breaking very weird as they not only snap but they are getting embedded into the table, very deeply and have to be removed with plyers. Finally, after 6 blades the pattern is cut.

It is important to mention that CS2-006 (Jac) was using this exact same path. In that case the path was cut with a single blade. We move to CS2-014 (Iv), which has less curvature and the path is successfully cut using only one blade. CS2-016 (Mic) path is next, which is a modified version of CS2-001 (Char).CS2-001 (Char) had to change the blade 2 times around the area of the horns so I expect a similar situation. I tell this to the participants, that I expect to lose 2 blades and they suggest to rotate the table as it seems to be the only parameter that could have changed if the same path was cut in the morning using the same end effector and same concrete material. We rotate the table 360 degrees to use the opposite corner which doesn't have any concrete.

The path starts to cut, participants bet in the number of blades that will be lost and CS2-028 (An) gets it correct we lose 5 blades during the cutting process. For the final path I suggest that instead of using the 'cycle seat' which might take a few blades we do another one of the paths generated for CS2-014 (Iv) which was done with a single blade. I know that the avocado took around 3 blades previously and with the current circumstances it might take over 10. CS2-028 (An) agrees and we do another cut of CS2-014 (Iv) path with a single blade, the cutting process takes around 2 hours due to the multiple stops, opening of the cage and blade changing.

With all paths cut participants start to hydrate them, due to the blade problem they suggest that hydration shouldn't happen on the same place where the cutting takes place. They suggest to do it on the floor over black plastic bags. I agree with this and provide them with the bags to protect the floor, the bottles of water to spray, frames and the stapler. In the meantime, I change the end effector and put new marks on the table for the positioning of the frame with the hanging cloth so that it corresponds to the position of the digital model after the translation and rotations are done in the grasshopper definition.

CS2-013 (Nad) goes first, she takes and initial scan and the robot gives her 246 points to push in relation to the expected digital model, she decides to run the robot pushing program. Then a second scan is performed and there are still considerable differences between the expected digital deformation and the current physical deformation, the participant decides she wants to do a manual round of pushing but asks to see where the points to be pushed are located. She manually jogs the robot to those points rotates the sphere to 'massage' each of them as the robot program does. A second scan is taken which shows proximity to the digital shape and only around 10 points in the higher part of the shape that need pushing. The participant decides to push them jogging the robot herself, although she keeps an eye on the rhino model and the grasshopper definition showing the points that are still above the digital simulation. She keeps asking me if she is pushing in the correct area of the rhino model. This participant since the robot introduction session became very fascinated with jogging the robot and is taking very long in her task as she keeps pushing, massaging and jogging. I am starting to feel nervous about the time as there are 3 more participants to go and is already 20.30. I offer her to do another scan to know how much deformation she has achieved to which she agrees. The third scan shows that the shape is now below the predictions from the digital simulation hence there are no points for the robot to suggest pushing. CS2-013 (Nad) seems satisfied with the result and hydrates her shell to leave if for drying. CS2-013 (Nad) did 3 scans in total, one run of a robot pushing program (initial points), and 2 sets of manual jogging for pushing.

The next is CS2-016 (Mic) who does one initial scan and decides to manually push his shape into position. After a round of jogging and pushing he is happy with the achieved deformation and doesn't want to do any more scans. The participant did one scan and one session of manual jogging for pushing.

CS2-014 (Iv) does an initial scan and decides to run the robot program of the suggested pushing points. The end effector is too high and not reaching the fabric during pushing, after checking since the height was correctly calibrated for the morning participant and first participant of this session it seems that the participant hanged the cloth in the frame the other way around, the frame is slightly shorter in one direction and is designed to be used with the 30x40 face up. The height is calibrated in the grasshopper definition and after 2 tests the code is sent to the robot. A second scan is made which shows the shape very close to its digital simulation and the robot only suggests 20 points for pushing. The participant decides to do a manual push of this points during which the fabric rips towards one end of the shape he keeps pushing but decides not to do any further scans. The participant does a total of 2 scans, one automatic run of pushing the code generated by the robot and one iteration of manually jogging for pushing.

The last one CS2-028 (An) is not interested in the shape at all and only in the pushing process. He does one initial scan from the same position as everyone else and wants to do a scan from above. After this he does a little bit of manual pushing while I calibrate the height of the Kinect to the frame again. Once the robot code is generated, he wants to run it in automatic mode. As the frame is not bolted to the table, I am afraid that in auto mode the moves of the robot will move the frame from position making any further pushing inaccurate as the robot will be pushing certain distance in a different place from where that distance is needed. i.e. if the centre should go lower the robot pushing information for that area will be deeper but if the frame is moved the robot can end pushing lower in one edge, etc. Due to this I change the axis velocity to 50 from 100 on the cutting program and run the program at 30% of its full speed. We get out of the cage and start the program. The robot is smoothly pushing, massaging and moving at each point and the participant is saying that that is what he wanted to see, he seems very happy. He mentions that he really wanted the robot to push on its own. After one session of robot pushing the participant is satisfied, as the fabric rip on one end during the cutting process he doesn't think that any further scans are needed and once the robot is done, he enters the cage to hydrate his shape and leave to settle. In total the participant did one scan and one run of totally automated pushing from outside the cage. The pushing program is run with an **axis velocity of 50** and at **30%** of its full speed.

Participants leave around 22.30 with a session of more than 5 hours. They remained calm during the whole session even when the blades were continuously breaking and were always trying to help. I.e. scrapping table, rotating table. They mention that they really enjoyed it despite the late hours as it is their only chance to interact with the robot.

After participants leave, I order 35 more blades from amazon, they come in packages of 5 and need to recalibrate the pushing height of the end effector as one height worked for two participants and another one was needed for the other two otherwise the pushing sphere is crashing with the frame.

Observations: Differently from previous second year participants who refused the robot pushing program and decided to only manually jog the robot during the pushing process, all participants of this day did automatic pushing with one participant going as far as running the pushing sequence fully in automatic mode. This is contradictory to my previous observation regarding second year participants. Everyone from today is second year and they all embraced the suggestions of the robot about where to push and allowed him to push based on the comparisons between physical and digital models. CS2-013 (Nad) and CS2-014 (Iv) on their second iteration of pushing decided to do it manually but were keeping an eye on the rhino model as guidance and kept asking me if the points where they were doing the pushing corresponded to the ones in rhino. The first fully automated run of a pushing program also occurred. In both sessions, today it felt as if computers and humans where partners throughout the exploration process. Participants got a full understanding of the parameters that can go wrong, i.e. blades breaking, concrete accumulation on the table. They tried to rationalise them and offer valuable suggestions. They were patient and enthusiastic about the task staying on a Friday evening until after 22.00 working on the robot task and with very positive comments afterwards.

03.12.16

Preparation of the cutting paths for CS2-002 (Nik) who is due to come on Monday for her robot process. I re-export the locators from Maya, as the excel file with the coordinates has been behaving weird even when z-values are constant. On this export, I follow the same sequential logic used for the file of CS2-006 (Jac) to avoid as many singularities on A6.

Z-values are checked and replaced in excel to ensure they are all the same before exporting the coordinates to generate the robotic path.

During the afternoon, I prepare the files for the group of participants that are coming on Monday afternoon. All of them have asked for a design to be made for them. This time I think a good test will be with simple polygons to check how they deform. So far, we only tested a rectangle and the rest of the geometries have been random curves. I prepare and hexagon, a pentagon and a variation of the diamond shell which is a rotated square with fillet edges.

I use the weekend to order a lot of more rotary blades for circular cutter. 25 more blades are ordered.

05.12.16

8.00

Early arrival to school to test the robotic paths before the participants come, the file from participant CS2-002 (Nik) still has 2 singularities on A6 that have to be manually fixed. The other files seem to be running fine.

10.00

Participant CS2-002 (Nik) arrives for the robotic task. She cuts her piece of fabric and positions it on the table. We run the robot cutting program and the bottom curves didn't cut as she positioned her fabric higher on the table than from its position in the digital model, so the curves were outside the fabric.

Her file and cutting has really been a struggle, this is the fourth session for this participant. She cuts another piece of fabric and places it now in the correct position to be cut. The edge of the shape is not getting cut, the robot is only marking it. I lower it less than a mm and send it again. The edge curve is done separately and after two blades the whole file is finally cut.

The participant is happy as this cutting pattern has been a struggle and we hi5. She proceeds to hydrate and mount on the side. We protect the floor and the table as much as possible specially the table since now I am worried that it is deforming and we just flipped it with the last group so this side of the table is ideally kept dry. I mount plastic bags and mark on them the position where the frame needs to be in order to be sure that the digital and the physical models match.

We do an initial scan which doesn't show any deformation, meaning the physical shape is almost flat. The robot suggests a round of pushing all around it in order to make it approximate the digital simulation. The participant is happy with this and acknowledges that her shape looks flat as it is mounted currently on the frame. She agrees to do it automatically. We send the code and get out of the cage. The robot does a full pass of pushing and massaging all around the model based on the distances coming from the comparison with the digital model. The participant is happy to let the robot run and observes and takes images from behind the cage.

After the pass is finished, we go inside the cage and perform a second scan, the scan shows that all the points are now matching or below the digital simulation. The list of the robot task is empty. As the robot cannot push upwards if all the points are below or on the digital simulation it is configure to only show an empty list. The robot doesn't have any more points to push.

The participant is satisfied with the robot pushing and to see how her shape deformed to match the digital simulation. However, she decides to do a round of manual pushing and massaging by jogging the robot to certain areas. After this, she says that if she was to do the task again, she will go for longer curves as she was expecting a different result that from the one achieved. She hydrates the shape and leaves it to settle. In total the participant did 2 scans, one round of automatic pushing from outside the cage and one round of manual pushing.

14.00

The afternoon group arrives, it is formed of 3 Greek participants and one from Asian descend: CS2-010 (Kat), CS2-011 (Mar), CS2-020 (Soo) and CS2-022 (Pro). They have all asked for curves and designs to be generated for them which I did. The designs are shown to them. CS2-010 (Kat) has a hexagonal shell, CS2-011 (Mar) and CS2-020 (Soo) have the diamond shell which is a variation and adjustment from CS2-013 (Nad) design, and from the original CS2-006 (Jac) shell. Participant CS2-022 (Pro) also has a variation on a hexagonal shell.

Participants cut their fabric, and we start with the cutting paths for the hexagonal shells. This pattern only has a few fillets on the edges but are mainly straight so I assume that the blades will survive. Blades start breaking without any evident reason from the beginning. We have to open the cage so many times that the groups start a little game of who is the next one to go for the key and play turns. We replace 5 blades with the first two hexagonal shells. I am very worried as we move to the other pattern which has been cut before so it shouldn't be so much of a problem but the blades are not working well today. The first order of blades is from OLFA, but they come in packs of one and we used a lot when cutting CS2-024 (Ah) shape after that I have ordered unbranded blades which come in packs of 5 and the rest of the participants have been using them. The blade problem started to be very bad last Friday, reasons could have been the deformation of the table due to concrete accumulation and water but now the table is flipped and I cannot find any other reason of the change in behaviour. One of the participants suggests that the blades are too stiff so when the robot makes any kind of movement they break. Looking for a change of faith I replace the blade with an OLFA blade which seems to sort out the problem and the remaining two paths (diamond shell) are cut. Now it is looking as a brand problem but this also doesn't make a lot of sense as most of the participants have been working with the unbranded blades and until Friday they started to break like this. Very strange.

After all paths are cut we cover the floor and participants start to hydrate them while I change the end effector. Their digital models are already loaded in a layer with the name for each participant and in the rhino file to run the comparisons.

CS2-011 (Mar) is the first one to do the task. After an initial scan the participant decides to go for the robot automatic pushing. We run the file, but the heights of the Kinect are off again and the sphere is not touching the fabric. This is something very weird as all the frames have the exact same size. I adjust the heights 2 times and we get them right. There is also a problem with the plastic bags used to protect the table as they cause the frame to slide all over the place so we end up removing them and keeping the frame on top of the table with only a plastic bag on top to protect it. After the initial set of pushing the material seems to be below the digital simulation and the acceptable range for the robot. We do a further clean of the point cloud and the robot suggest 30 points that are still above. The participant says she wants to leave it like that and not do any further pushing although a small area is still above. I hand the teach pendant to the participant in case she wants to do some manual jogging but she seems rather uncomfortable in using the robot, tries to jog it but gives up after 5 minutes and says she is happy with the shape. This participant seemed in a hurry to finish the task, didn't come anywhere near the robot even after I handed her the pendant gives the impression of being generally uncomfortable around the machine. She does a total of 2 scans, 1 round of automatic pushing and none jogging for manual pushing. Participant looked uncomfortable when she had to jog or approach the robot.

CS2-022 (Pro) asks to be the next one as he has a meeting with his design tutor after the session and wants to finish. He seems very engaged with his geometry even when he didn't design it and after an initial scan he asks for the model of the digital simulation so that he can have a look and aim for a similar deformation. His shape after hanging is very flat so he asks if he can first manually jog the robot for pushing. He expends a good amount of time positioning his frame correctly and I explain him how to do the rotation with the sphere at each point in order to 'massage' the material and he engages with it spending around 25 minutes manually jogging and pushing. The participant keeps the rhino model up with the comparison scan to see at how the digital model deformed and tries to achieve a similar outcome manually. He then asks for the code to be sent to the robot which he runs manually and making more emphasis in areas that he thinks he need to. After a long round of pushing we do a second scan and it shows a lot of deformation from the initial flat state, and from how it started before he did the massaging. The participant asks questions about the comparison, go definition and the point clouds. He only gets 3 points above the digital simulation. I explain him how as some of the rest are lower or match the digital simulation the robot cannot see them and it is only sending a code with 3 points. I tell him he did a very good job being the robot. The participant is happy that both match and leaves it to dry. Total of 2 scans, one round of manual pushing and one manual run of a robot pushing program

CS2-020 (Soo) comes next with a diamond shell. We do an initial scan and it shows the shape to be very close to the digital model. The participant is engaged looking at the comparison and asking about the rhino geometry and how we generate the data to compare both point clouds. CS2-020 (Soo) finds it surprising how both shapes -physical and digital- are very similar, and only few points need to be pushed, basically the robot shows 2 points. We spent a lot of time going through the digital workflow as the participant asks many questions regarding how the point cloud is taken, compared and how the robot knows which points are above. She is also asking how are point clouds matching and how the robot code is generated. She asks to do some manual pushing but keeps asking questions of the digital workflow. After I explain her how it works we decide is better to first send a round of robot code so that she can experience the full workflow. We prepare the code and send to the robot but she decides to run the program manually in teaching mode. This takes a long time. After finishing the program, we take another scan which shows no more points above the digital shape hence no program from the robot. The participant does some manual pushing and leaves the shape to settle. In total, we did 2 scans, one manually run robot pushing session and one short session of manual pushing. The participant was very curious and engaged with the computational side of things and how the workflow was working.

CS2-010 (Kat) is the last one from this group to do the task. She also has a diamond shell and after the first scan the robot shows that the shell is well below the digital simulation and there is not any code to send. The participant decides to do a round of manual pushing where she pays special attention to the central areas of the shell. We do a second scan to compare how much deformation she achieved between the initial condition and after pushing and it shows that she did push a lot specially in the central areas. Participant is satisfied and leaves the shape to dry. 2 scans, one session of manual pushing.

We proceed to the interview and questionnaires. The session ends by 6.

Observations: Now the problem with the blades seems to be related to the brand, I am thinking that the non -branded ones are stiffer and hence break immediately whereas the OLFA ones are a lot more flexible but also a lot more expensive. I try to order more but they won't be delivered on time for the Wednesday participants. I have 3 remining olfa blades, and the one on the blue pizza cutter that I ordered and around 20 of the non-branded ones. It is still not clear how a lot of participants used the non-branded ones without so much trouble.

06.12.16

Meeting with Wassim to discuss results so far (copy notes). We discuss that initially it seemed as if older students were more engaged with the feedback loop and able to give some control of their design to the robot whereas younger students want to do the pushing manually and keep in control of the design in a less digital way.

Wassim suggests that is not a difference between younger an older student but their lack of experience and systemic thinking that makes them want to control the robot and process themselves. As students become more mature and intellectual about their design process, they get over the novelty of the robot and want to see it gain agency. The maturity and ability to intellectualise the design process seems to not be related to their design year and more of a personal matter. Some students lean naturally towards digital processes which make them interested in seeing the computer and the machine gain agency.

Wassim suggest looking at clustering algorithms for data analysis and to ignore the extremes as some participants i.e. Bartosz got extremely upset and totally blame the robot for all the problems on their design and geometry.

Through the data analysis, I should try to find where and when in their design process do humans feel like they can transfer agency to the robot and answer: At what stage of the design process do designers give control over their design? Which kind of maturity do they need?

The rest of the day is spent preparing curves for the 6 participants of tomorrow. 3 of the afternoon participants and one of the morning participants sent their design and curves in advance. This makes it more complicated as I need to fix their files and curves to make them cutable for the robot rather than adapt one of the working patterns. I create a pentagonal pattern for the 2 participants that didn't sent a pattern to keep testing different geometrical shapes (hexagon, diamond and square are done).

Participants CS2-027 (Alex) and CS2-019 (Anas) sent their patterns after 9.00pm so now I have patterns and designs from all 6 participants but also a long night as the curves in the patterns need to be fixed. Pattern deformation simulated and converted into robotic paths. The pattern of CS2-027 (Alex) is made mainly of very small curve pieces and won't work with the robot as it won't be able to cut with the blade. I decide I will let him know this tomorrow when he comes for the exercise and speak to him about doing the pentagonal shell which I believe can produce interesting results.

07.12.16

Early morning start to: check the paths of all participants, run paths and double check to correct any potential 360 degree rotation on the fabric, re-calibrate the pushing height of the sphere end effector after some of the misses from Monday, load the shell simulations with each participant name in the rhino file on the robot computer to be sure that they are ready for comparison, demount the shells that are drying on the frames from the Monday session and cut fabric for all 6 participants of the day in order to avoid delays during their sessions as both groups are back to back.

The table also has to be rotated as it has been left the other way around (bad side for cutting -decided on previous session- by the filming crew that came yesterday)

14.00

CS2-017 (Jan) and CS2-027 (Alex) arrive. I explain to CS2-027 (Alex) the situation with his path and we run it once so that he can see how the robot would not manage to cut due to the very small curves, also a pattern of this nature won't deform due to the huge concrete losses. He agrees to do the prepared pentagon pattern instead. The pattern of CS2-017 (Jan) will have a similar problem in some identified areas where the curves are very small. This was discussed with her previously and she didn't want to change her pattern. Participants also see the simulated and expected results of both patterns. As the fabric is already cut for them, they only need to place it in the correct place for the robot to cut, we do an air run so that they can see where in the table are their paths located.

CS2-017 (Jan) is the first one to cut he path, one half of it is correctly cut but in the other one the blades start to break even when doing a straight line, the problem is more acute than ever before and the explanation of it being because of the concrete accumulated on the table is not valid as this has been fixed. We run very small straight lines and the blades still break. After 5 blades the participant suggest bringing a cutting mat from the studio to place below the concrete. We push the path up in the z by 3mm which is the thickness of the cutting mat but blades keep breaking. We try to run the robot cutting slower at 70% of the speed but blades keep breaking. After 10 blades and trying different solutions as the cutting mat, the speed of the path, the blades are in no position to cut even a small and straight curve. There are only 4 olfa blades remaining and 6 participants but the current blades are not going to be able to finish the job. We change for the olfa blades, the first one breaks after a few curves but manages to at least cut some curves. Demounting the blade from the extra rotary cutter (the blue one that couldn't be mounted on the end effector due to different handle) gives us an extra olfa blade. We demount and use this one with which we manage to finish the path after around 12 blades, this has been the most painful path so far. The path in itself looks symmetric but it is not, one half of it was easily cut and has complete curves with joints in-between them, the other half where most blades snapped is cut to pieces and shredded in some areas, the curves on that half were smaller, sharper and with smaller joints, these plus the constant blade change and snapping contributed to the fact that this side is in shreds at some areas. The blades with no brand were snapping even with the straight lines so the problem is definitely on the brand.

The pentagonal pattern of CS2-027 (Alex) is cut with the olfa blade currently mounted on the robot. CS2-017 (Jan) says that she wishes she had done that pattern, I offer her to cut it again but she refuses and wants to see how her pattern comes out. But she can see how the small curves are causing problems from very early stages of the fabrication process and mentions that she didn't consider how the blade would behave and how one half came out very good but the smaller divisions don't really work out. CS2-027 (Alex) says that he is happy with his pattern.

Participants proceed to mount their shapes into the frames while I change the end effector.

CS2-017 (Jan) is the first one. We do an initial scan and she decides she wants to do some manual pushing as the fabric has turned to shreds in some areas during cutting. The participant is in general very comfortable with the robot (since her first session) and she moves around, squats to see deformation and has smooth control over the robot movements. She is also comfortable doing the pushing manually and has a smooth control over the robot, not any hard-breaking and in general good deformation. A second scan is taken which shows that the achieved deformation after pushing is similar to the simulation on one half of the model (where the pattern didn't tear) on the other half the scan shows the fabric beyond the digital simulations, this is due to tearing and the participant understands it as such. CS2-017 (Jan) happy that half of the model worked, whereas the other half due to pattern and blade problems makes her unhappy. She mentions she will be happy to redo it, modifying her pattern now that she saw how does it work and the problems that the pattern represents for later stages of the production process. We agree that even when I tried to explain how the pattern affects the deformation and the cutting it isn't obvious until they try it by themselves and see it. 2 scans, only manual pushing.

CS2-027 (Alex) goes next. We do an initial scan which shows the shell as very flat. We run the comparison which shows all points above the digital simulation. The participant asks to do the automatic pushing with the robot, so we generate the code. The robot is run with the cage closed in auto-mode. After the whole code runs we do a second scan which shows that very good deformation was obtained after the pushing and both shells (digital and physical) are very close to each other. The participant doesn't want to do any more pushing and he is happy in leave it to settle as the shape is very close to the expected deformation. I ask him if he would like to do some manual pushing to deform some areas or change the design but he refuses and says he is happy the way the pattern worked and he is very happy about how the shell turned out. 2 scan, no manual push only auto.

The session lasts 3 hours so I have to email the next team and delay them until 5. The problem with the blades made the process particularly slow. Both participants sent their designs in advance, one of them I modify to improve as the curves sent by the participant are extremely small and won't be cut by the robot. This participant ends up being happier about his pattern than the participant that designed and cut her own pattern, although she was warned in the third session that some problems might occur due to the distance between the joints.

17.00

The second group of the day formed of CS2-007 (Chen), CS2-009 (Vel), CS2-012 (Ele) and CS2-019 (Anas) arrives. All of the 4 sent their curves in advance so we are not sure how the patterns will behave in relation to the blades. Due to the previous experience, I suggest that we start by cutting the patterns of the 2 participants that have mainly straight lines CS2-007 (Chen) and CS2-009 (Vel) before doing the patterns of CS2-012 (Ele) and CS2-019 (Anas) which are made mostly of curves. The pattern of this last participant is of special concern as the curves are very sharp on the lower and bottom ends. Participants agree to this and we do air runs of their patterns so that they can know where in the table to position the fabric.

CS2-007 (Chen) is the first one. His pattern gets cut on the first run and by only using one blade. The olfa blade left on the cutter from the previous participants. 1 olfa blade, no breaking.

CS2-009 (Vel) goes next. Her lines are mainly straight with some fillets around the corners. The blade breaks and I change it for one of the non-branded blades as I am aware of the shortage of olfa blades and we still have the participants with the more complex patterns missing. The blade breaks almost immediately and has to be replaced again. Another non-branded blade is used but it also breaks after doing 2 cuts. We replace it for an olfa blade. I warn the participant that if this blade doesn't make it, we might need to change the pattern and she can do another version of CS2-007 (Chen) pattern. We will also have to move on and try some of the other participants' paths before we run out of blades with hers. The participant agrees that this is almost like a last chance situation for her pattern and complains that the robot doesn't like her although she has always been in love with him. The other participants make fun of her and the fact that she might have mistreated the robot in the past. The olfa blade thankfully is able to finish the job. The pattern gets cut with 2 non-branded blades and 2 olfa blades.

CS2-012 (Ele) is next. I am a bit worried about her design and I let them know so. The participant asks a very interesting question regarding how the order of the curves affects the way the robot cuts them, as she realises that the cuts are being done by quadrants rather than in a sequential clockwise or anti-clockwise order. As the curves are concentric this second option will make sense but to avoid the singularities in A6 I have chosen to select the curves by quadrant, since problems started with the first participants if the robot tries to go around. She is the first one to realise and ask about this. The blade breaks and is replaced by another olfa blade which gets the job done. 2 olfa blades.

CS2-019 (Anas) is the last one to cut her design and the one I am worried about the most due the curvatures. We start an although some scary moments, the robot manages to cut the whole path using only one blade. The participant attributes this to the fact of the robot 'liking' her although she doesn't like any of the parametric design units or way of thinking. She says that because she is not too pushy in getting the robot to like her, he likes her. This is very surprising as I was expecting another blade shed with this pattern. There might be a relationship between curvature and blade survival. It is very strange that the blade had problems with what was basically a straight cut with this group and they are easily doing curves. Blades have had problems in the past with the curved patterns so is not a straight vs curve problem, but there is something going on. 1 olfa blade, no breaking.

Participants proceed to hydrate and mount their fabric on the frames (this is done in the floor using plastic bags to cover it, as has been done since the team from the 2nd) while I change the end effector. The pattern from CS2-009 (Vel) is deforming already a lot hanging very low just after hydrating without any pushing. The participant is worried about the massive difference already obvious between her simulation and what is happening and she is wondering where did she go wrong or how could she have gotten it so wrong. This is also the first one I see. Square patterns in the past have not being flat but also haven't deformed as much. This might be one of the most deformed shells really hanging below what was expected and what has been expected from the material generally across the experiments. Participants are wary of how the concrete seems to repel the water rather than absorb it at first. They are advised to hydrate the cloth flat on the ground and hang it after. Also, to wear gloves and throw water into the cloth pushing it with their hands to start the hydration process. Once the concrete start to hydrate they can use the nozzle spray to keep hydrating it, but initially it needs help to start soaking water.

CS2-012 (Ele) is the first one for the deformation process. We take an initial scan and she is interested in seeing how the robot pushes the fabric. The robotic code is generated and ran in auto-mode from outside the cage. After the code is run the participant decides to do some manual pushing before scanning again.

She has a good control over the robot and jogs him with some hard-breaking when she feels that the robot is going to low or when she is changing between jogging modes, there is also a lot of stop/go motions. After her round of manual pushing, we do a second scan which shows that the physical model is lower than the simulation. I show her that the robot is giving her an empty list of points as he is operating within a range seeking for points above the simulation. The participant is happy and decides to hydrate the shell and leave it to dry. 2 scans, 1 round of auto-pushing (outside the cage), 1 round of manual pushing.

CS2-007 (Chen) is the next one. His shell is also based in a square pattern and hence straight lines. Distance between cuts in some of the quadrants is very little so the shell is hanging a lot. We do an initial scan which shows that the physical model is lower than the simulation. We generate the robot code as the participant is interested in the grasshopper workflow which is explained to him step by step. His simulation is very shallow so when we run the code the robot is not going low enough to touch the actual physical model. He runs the code and sees how does it work, also how there is a rotation and a lift after each point. He realises of the problem due to the difference between his simulation and the physical model and why the robot cannot reach the physical model with the generated code. The participant is very interested in the digital workflow asking very detailed questions about the process. He decides is better for his case to do a round of manual pushing due to the condition of the fabric. The participant feels very natural and comfortable around the robot and doing the pushing. He spends a lot of time pushing and fine tuning his design and often asking questions about whether he is doing it correctly and if it will deform as he expects. Almost 30 minutes of manual fine-tuning. In one push the participant gets confused between the jogging modes he is and pushes two low in the z-value which causes the wooden frame to break in one of the joints (a screw came off) but luckily the fabric doesn't break. We fix the frame and the participant keeps doing his meticulous pushing. He agrees to do a second scan just to check how much the fabric deformed with all his pushing from its initial state. A comparison to the digital model doesn't make sense as the digital model was very shallow to start with and already off from the initial physical conditions. The participant is happy with the achieved deformation, very much different from his initial design and from the initial state of the fabric and decides to hydrate it more and leave it to dry. 2 scans, 1 failed attempt for auto-pushing (the robot wasn't reaching the fabric), 1 long round of manual pushing.

CS2-019 (Anas) comes next. We do an initial scan and perform the comparison which shows that the physical model is shallower from its digital counterpart. The participant decides to do a round of auto-pushing from outside the cage. The shell achieves a very nice and deep deformation after the code is run which the participant appreciates. We do a second scan which shows that the shell is below the digital simulation. The participant asks for manually pushing in some areas where she wants more deformation but is happy with how the shell is looking. After a round of manual pushing, she doesn't want to scan again. I offer her to compare the deformation after the robot pushing session with the deformation after her pushing session but she declines arguing that the shell is below from the digital simulation and that she likes it the way it looks. She says that she is not a parametric lover but loves concrete and enjoys how the concrete can achieve these curvy shapes. The shape is hydrated and left to dry. 2 scans, 1 round of auto-pushing, 1 round of manual pushing.

CS2-009 (Vel) is the last one. This participant had a meeting with her year chair so she left after hydrating and hanging her shell. Her shell is showing a great deformation, it is hanging a lot although the cuts didn't break or shredded like in other cases, but is still far from the digital simulation and from the previous observed behaviour of the material. I believe that because is a mesh and everything is connected the fact that one corner got slightly over-cut (beyond where it should) is causing for the whole shell to overhang. However, the participant thinks that is because of the parameters she used in the digital simulation. Her theory is not very clear as almost everyone has been using the same parameters and is the first time that a difference between both so big is observed. The participant takes longer than expected in her meeting and by the time she comes back all the other participants are done and have left and her concrete shell has started to settle. She decides to take one scan, and get a mesh of the scanned physical concrete which as expected shows great deviations. The participant decides not to push and comment on how the robot doesn't like her despite her efforts to make him like her.

We do the final interview with CS2-012 (Ele) and CS2-009 (Vel). The other two participants left before. CS2-012 (Ele) comments on how the robot becomes alive when you try to do something with it. Whereas he usually looks like a dead machine and says this is something she enjoyed very much. Both participants decide that the robot is a 'she' as it is very moody. The session finishes at 11.00pm. All participants from this session sent their curves, simulations and designs in advance and were generally committed to their designs and excited about how they coming together. Participants were also filming the robot throughout the session during the cutting and pushing processes of their shells. This is the last group of participants.

APPENDIX L RESEARCH NOTEBOOK 2

Notebook 02, the data (Latour 2005)

For gathering information in such a way that it is possible simultaneously to keep all the items in a **chronological order and to dispatch them into categories which will evolve later into more and more refined files and subfiles**. Record the movements through one frame of reference to the next (Latour 2005, p.134).

This notebook is where the data is kept. This notebook is the easier to keep with a computer qualitative data analysis software (atlas.ti) The software will allow to tag the text by paragraph or single words and query it. This notebook corresponds to the data as coded in Atlas.ti. During this research, notebook 02 was divided into eight different notebooks each related to a specific aspect of the collaborative design exercise: 1)design background of the participants; 2)feedback; 3)robot features; 4)designing with robots; 5)robot elements; 6) external things that bothered the participants; 7)benefits of the robot arm; and 8)reactions to robot arms.

Notes and comments were collected and classified into the appropriate section.

Design Background of the Participants

This document is thinking how participants usual attitude to design influences their interactions with the robot arm. I have the preconception that participants used to do working models versus the ones that only do one final model to represent their design will be more positive about getting feedback from the robot as they see the model not as a final product that they could consider 'precious' but as in work in progress to test and refine ideas.

In this scenario models can break, change, they have an influence and inform the design continuously rather than only represent an idea.

When designers only want to represent their preconceived idea, I speculate that they won't consider the information or feedback given by the robot useful. These notes are to be correlated with the videos and field notes regarding their reaction to the second scan:

Did they just leave?

Did they try to achieve (through manual pushing or automatic robotic pushing) the initial idea

Did they go outside the initial idea and were happy to try different variations?

Did they go outside the initial idea and were upset about the differences / didn't embrace variation?

06/02/2019 12:28:26

Very interesting point, they are normally used to design **the final 3D shape of how something will look like, here they were designing a 2D pattern from which the form would emerg**e. This flip on the design process was causing them conceptual problems. I didn't foresee this.

This could be attributed to a lack of maturity on their design skills or maybe to a different way of design thinking all together.

Systematic or parametric design thinking would emphasize designing the parameters that create the shape rather than the shape, something that students haven't been introduced to conceptually.

06/02/2019 12:45:50

Some participants, even when they said that they do models they mention that only ' to see how it looks like in 3 dimensions' this seems to suggest that they are not allowing for any feedback from the models and into their design process and they are only being used to confirm preconceived ideas. This is a new variable to be introduced to the analysis

06/02/2019 12:48:54

Participant feels precious about physical models, a common problem in architecture students, she prefers to avoid models altogether as once a model is made would be hesitant to change it. This, I would argue, shows a lack of design maturity or of an understanding of working models (common in some architectural schools, so might not be due to the student at all) this is the same participant struggling with the idea of designing the system rather than the final shape, worth checking her year of study and background

On a second thought, after reading the rest of the interview of CS2-005 it could be faster to redo a model if it's done by robot hand than by human hand, we didn't explicitly comment on this but could be argued.

07/02/2019 15:28:48

Cs2-012 notes that she hasn't been taught architecture in a way of exploration and design by making models, so she finds problematic using the robot to do tests or on the early stages of the design. She would feel more comfortable using it when she already has a building. The background of the participants has great impact on how they feel about the robot and about the proposed collaboration.

08/02/2019 08:01:46

Participants finding confusing that they have to design the 2D rather than the 3D, this is the second time this is mentioned, both by a 2nd year student. Although, CS2-012, third year mentioned she was never thought to design in this way but didn't clarify if the 2D-3D or an experimental, form finding way

Cs-019 older participant very much engaged in material processes and making models. It might not be a clear divide between 2nd and 3rd years but there is some level of maturity to allow for models to become important. Models might not need to be physical representations also digital 3D models that can keep changing and being modified.

08/02/2019 21:41:39

Participants that engage with the process of making models and are positive about making them to understand 3d space see the robot as an opportunity to do models and perform tests on them faster. This starts to be a crew more interested in the potentials of the arm as a design aid.

On the other hand, some participants are less positive about having it as a tool during the design process and do see it as a production tool to make models at the end but not through the process. A tool to fabricate their final model. They also tend to be less embracing of a digital design process and tend towards sketching as they feel that having to use software restricts the way they think and constraints their space of possibilities. (020, 022) This can be argued as people that feels more comfortable in one medium (analogue or digital) will feel constrained in the other one, which won't offer them the same freedom, mainly because they don't have the same mastering of the skill on that medium.

Feedback

I am trying to start this memo now, as the issue of the feedback and designing with robots seems to be getting tangled, will try to untangle them from now on.

06/02/2019 12:54:16

Interesting observation that the feedback might not need only to be related to the physical - digital model but can also be used to test material or weather condition and use the robot to simulate different environments

The feedback is more efficient in detecting differences than people

Participants express that feedback is one of the best things about the robot to see variations between their digital explorations and what actually happens in the real world. They feel it gives them an idea from which they can then investigate the factors of why the models are not matching. Interesting point about being a starting point for further research

07/02/2019 13:53:17

Participants that are less materially orientated, they don't care about exploring material possibilities, etc. They still find the comparison between digital and physical extremely interesting to achieve through the formation process

07/02/2019 15:39:04

Participants tend to say in the interviews that the robot was giving them information about the deformation that they couldn't judge by eye, but in the questionnaire a lot of times this is contradictory, they tend to be positive about being able to decide the material information just by what they see

08/02/2019 10:18:47

The feedback made this group confused, was there an error during their exercise on the calibration of the tools? None of the other participants had this confusion regarding the feedback

Feedback when the physical and the digital are not so far off becomes exciting for the participants. They can see more detail when they see the scan of the model and realise it is closer that what they thought to their designs. Most of the time they are not aware of how close or far it is unless something dramatic happened, like in the cases when the fabric ripped and it was very obvious it was far from the digital. In most of the other cases participants do express surprise to see how they are matching.

They do agree that the mind is tricky and they need from quantitative information to see the changes, or simply to take a step back and see through some other glass what is happening.

08/02/2019 21:32:56

The accuracy of the deformations that the comparison between physical and digital provides and the insights of this are attractive to a good number of participants. Would be interesting to classify them in terms of year of study and design skill.

Robot Features

Thinking how the physical attributes of the robot influence the participant, the way they relate to them and the way they think about them. Positive features that participants enjoy when working with the robot

04/02/2019 14:07:46

I thought smaller robots were more compelling to use as they appear more friendly, in my opinion also, they don't brake as hard so it doesn't feel like such a big machine. Participants seem to think otherwise, they like the robot because is big and that makes them feel good about it .... interesting though to research

04/02/2019 18:26:44

The fact that it instantly reacts and stops if it thinks that you are in panic made the participants feel that it was a reliable partner - CS2-002

05/02/2019 11:08:19

The possibility of manually jogging the robot in a path that you want to and do something with it on that path, makes it a convenient partner that can be used as a stronger, more precise 'third hand' but it won't substitute your primary hand // it cannot be a primary hand comment expressed by CS2-003

The participant feels she can trust the robot because the robot is stupid - it won't know how to hurt her (interesting point i.e. smart robots are scarier)

05/02/2019 17:14:01

Another participant finding the size of the robot highly encouraging!

06/02/2019 12:13:49

Quick

06/02/2019 13:15:37

The fact that the robot doesn't move from the floor (is not walking around) made participants feel safe and reassured.

Strength of the robot, was described as good in the case of this exercise in two ways: 1) the robot could do the cutting a lot faster than what participants would be able to do 2) the robot would keep pushing the material even when it was harder up to breaking point and beyond. Participants might be able to have done this second thing but they feel they would have been more careful and may not get the material to its limits as the robot would.

Potentials of what you can with technology, eye opener towards a different world

07/02/2019 13:55:02

Initially participants have a positive feeling about the robot - he hasn't done anything to them to break this circle (unless their design wasn't cut properly or the robot pushed to hard so that it broke) in participants with a successful concrete shell; they don't express any worries about interacting with the robot nor changes to its size, appearance, etc

However, they do immediately mention that the robot is safe ' as far as they understand it' giving the impression that this is not a definite answer, there is some worry left.

Feeling comfortable about how it looks, moves, acts, physical attributes of the robot are not having a significant impact on some participants

08/02/2019 10:46:26

Is difficult to know which way it is working (looking) suggestion to give it an aunty face, or a laser, a tool to indicate which direction it is looking at or is going to move towards.

08/02/2019 15:40:46

The robot as a machine that can allow them to build things that they wouldn't be able to build manually and to test new things due to his strength or overall perspective

10/02/2019 17:16:44

Repeatability and mass production are positive qualities that the robot can bring to the design process on the iterating phase. This is a very interesting comment and that not a lot of designer mention, the repeatability of the physical form finding procedure mediated by the robot. This is also something that designers working with robots don't practice often.

Designing with Robots

Thinking about the main issues that designers face when working with robot arms

04/02/2019 14:00:14

CS2-001 (Char)

The interface and difficulty in translating their thoughts into robot/machine motion. Experience could be a big factor on this, besides the unfriendly interface, teach pendant, etc.

CS2-002 (Nik)

Designers have to think in advance about the motion.

Designs have to be thought of in a way in which they could be done by robotic arm

If the design is too constrained, the possibilities to explore with the robot are less. The design needs to have some openness to it (less constrained design) so to explore with the robot

05/02/2019 10:48:47

CS2-003 (Val)

Design takes most of the time that you spent with the robot

Forces you to be more precise about what you want to do in advance

You need to engage with the material possibilities from early on (this response suggest that the student only engages with the material at the end or is too young/inexperienced)

It's like a third hand that can be stronger and doesn't get tired (enhance some human features)

It can give you a lot of accuracy if you want but it can also be used in a more playful way just to discover things

Manual control and pushing became very playful, the participant stopped thinking about the design and became engaged only in playing with the machine -- this could suggest and alternate path to discovery // design discovery

The feedback was very useful but she didn't engage with it as the participant wasn't looking for accuracy but only to have fun and test the playfulness path that the machine offers

05/02/2019 13:48:36

CS2-004 (Epa)

You need to insert specific points on your design to allow for the robot to do it correctly - talking about having to add extra points so that the robot goes up and down in-between the cuts. The issue of having to think about how the machine will do the path is difficult for the participant but gratifying as in it makes the cuts more precise

Elements that need to be added (points outside the curves, etc) to generate the robot path and which are outside of the design path can be complicated- it seems that for the participant thinking in a machine-orientated way was producing a lot of confusion. (i.e. he has to generate points that are not only for the robot to follow the design path but that include robot tool movements.

Design aim changed after starting to get feedback from the robot about how the material was deforming

06/02/2019 12:07:09

Cs2-005 (Sim)

the robot sometimes doesn't do exactly what you want him to do. I believe the participant frustration here can be mainly due to a lack of knowledge in two fronts:

1- robot motions and capabilities

2- design intent

Knowing more about the robot might not be enough as knowing more about the design process.?

Cs2-026(Gian) goes along the same lines, feeling that when he does something, he can do it exactly as he wants whereas the robot might not be able to do exactly that or might destroy something.

The lack of sensors is a common topic, basically that it can keep pushing the material until it breaks unintentionally. Some participants refer to this as the lack of 'intuition'. Some other participants see the design advantage of this condition to test materials until their break, simulate harsh conditions, etc.

The robot need of precise information is another of the topics that comes up frequently, designers would like to be able to just tell the robot 'do that side exactly as this one ' without the need for the precise coordinates and code that define how to do that.

What the robot can do might not match designer expectations. I would argue that is the case with almost any machine. It will have specific capabilities and limitations. There is something about the word 'robot' that entices participants to thing that it would be able to do absolutely everything. This is perhaps related to the image that the media has built around them and which leads to a misrepresentation of the robot capabilities and hence frustration that they are not limitless.

07/02/2019 13:47:55

The design and preparation time continue to be a concern for the participants. Is difficult to untangle if they would rather have more experience with the digital design tools or with the robot to feel more comfortable

CS2-006 makes a point that although the task was fun and enjoyable, he still doesn't feel that he would be able to do a full robotic design workflow on his own and that is what makes him uncomfortable

The issue of practice and sometimes steep learning curve can put some designers off from working with the robot. The question will be if the steep learning curve is related only to the use of the machine or to what would they do with it, if they were to have all the knowledge. More practice would be desired

07/02/2019 14:38:24

First person to comment on an important issue, that although the learning curve looks steep you only need to do it once. The rewards will outdo the initial limitations as once you learnt how to use the robot you can do multiple things with it. (Cs2-009)

Other tools like grasshopper give the participants initial results from the first day as they can be playing around with them. They feel that the robot is not a tool that will give initial satisfactions by just playing around with it.

The code and scripting needed are again described as the most challenging thing of working with the robot. The rest of the process feels straight forward to the participants.

Participants (cs2-009) would feel comfortable working with it if she had help, not on her own, but having someone helping with the code will make her happy.

CS2-009 notes that if she was to do something not too crazy, she would use the robot. This due to the precise information that the robot arm requires. It is understandable that designers won't feel like they have this kind of precise information on the early stages of their design process, when the aim is one of exploration and discovery. This point hasn't been explicitly touched by other participants but I feel it might be a common sense when they talk about the difficulty of the code is related to the difficulty of the thinking of what to do.

07/02/2019 15:43:10

'Robot is doing its part of the contract, it's just the fact that I've fucked up everything' CS2-009. A good point that the robot would do whatever you tell him to do, even if that is the wrong information what you are sending it.

07/02/2019 16:34:13

Participants have expressed three times (001, 006, 012) that if they were to redo the task, they will try to push further the limits of the robot (more curvy curves, push more, etc) the robot is encouraging them to be more experimental or get of the safe area of their designs. This can be a very positive discovery!!!

07/02/2019 16:52:14

I find a lot of constant contradictions between how participants say they feel in regards to the robot: that they require more experience, they cannot do the task by their own, they want support, etc and their answers to the questions 15-18 of the questionnaire where they have generally selected that they would be unconcerned if the task was more complicated. They have also selected neutral about how would they feel about the task if they had more experience and they generally seem positive about their ability to do the task even if it was more complicated, something not reflected on their interview answers. During the interviews they sound a lot more concerned about doing the task without help and generally having to work with the robot as they feel they don't have enough experience.

08/02/2019 07:54:31

The feeling that is tricky for experimentation keeps coming across, basically because it needs from precise information which makes the participants feel that they need to know exactly what they want to do in order to use it. This can be argued against by thinking on methods of algorithmic design, in which they have an idea of what they are creating but don't know exactly what they want and they still get results (e.g. when they use grasshopper).

08/02/2019 08:08:11

'Robots will do what you tell them to do not what you want them to do', participant comments this to express the difficulty he is having translating his thoughts into robot motions or robot commands, he feels he told the robot the wrong things (Cs2-009 had the same problem. She referred to how the robot did everything she asked, it was her who asked it for all the wrong things).

08/02/2019 10:02:42

Participants talking about how the robot would be good for something super abstract, if they knew its motions and then they would imagine how to build this abstract thing. Weird considering the particularities of the robot arm and performance on non-abstract very real things.

08/02/2019 10:30:09

This is the fourth time that participants refer to the robot performance as 'the robot did his job perfectly' and they blame themselves or the tools for the problems on the task

Keeping it simpler is something that has come across as what designers would improve if they do the task again. This means allowing more agency to the robot and the material rather than trying to keep all the control to themselves. This is a very interesting finding and something that could be explored further in the design process, the idea of designers allowing for other elements to join during the design process rather than the more traditional approach or imposing a design.

08/02/2019 19:12:31

Janette Vertesi talks about how the more humans work with robots they start to express and move themselves doing robotic motions, the way the designers of the rover talk in the lab at NASA is by gesturing and doing movements that correspond to those of a robotic arm, for a newcomer is difficult or funny to see how the researchers are communicating without having seen the robots. Participants after a few sessions seem to start getting a degree of techno-morphism as they start to get more comfortable jogging the robot, understanding its coordinates, and start to talk in robo-talk with their physical motion..

08/02/2019 21:28:35

One participant (CS2-011) mentions something desirable when using a robot for designing would be if it learns more about the cutting. This could be a link to the machine learning chapter. This is a very valuable comment starting to speculate that if the robot could provide insights or some further information than a scan, which is already in itself valuable and a lot of participants commented on that, but other knowledge and possibilities would open if it gives further insights. Although, there could also be negative consequences if they start to see it as a smarter machine as a lot of the participants find it trustable because it is stupid.

10/02/2019 17:11:17

Understanding the material behaviour and being able to quantify it through the robot (knowing where to push, cut, how much and the subsequent result) is something attractive to the participants on a design process that includes robots. Also, to quantitatively match the digital and the physical outputs. They feel that the robot will open future material understandings or possibilities after seeing how it works through the robot hand. They also emphasize the repeatability and rigorous experimentation that can be achieved by the form-finding process mediated by the robotic manipulator.

A valuable comment not often mentioned, but perhaps implied, is that the robot can allow for a better understanding of the digital world, is a bi-directional feedback, the robot is also allowing the human to have a better understanding of the material and also of his/her digital design process.

19/02/2019 11:07:33

Participants noting that when the design on the screen forms can exist feely without any gravity, material, or any constraints whereas when they work with the robot, they need to engage with the material

'sometimes the robot does what you want him to do, other times it does what it wants to do, it has its own personality' CS1-03

An older participant and with more design and work experience, he notes the possibility of using robots during the design process as a test ground to then using them for construction. A tool to bridge the gap between both worlds, something that the younger participants never mentioned.

The participants who are working architects find the robots as a tool to renew their enthusiasm in architectural design as they start to explore novel possibilities. Although, working architects are less likely to do models during the process. They do models mainly for representation purposes they find a new interest on understanding robotic working models as something that can give them feedback to the design.

'We always try to dictate the rules (like in life) but we are not always on control, if we know how to be flexible to the constraints, we can achieve more interesting results' Cs1-005

Less control over the shape and allowing more robotic agency results in better geometries. This could also be phrased as working with the robot rather than constraining each of its moves.

Cs1-006- noting that including the robotic constraints in their design (motion range limits, etc) which they thought would reduce their possibilities, actually ended up giving them novel, unexpected design solutions

Noting that the difficulty is not always on changing the design but in including all the robot parameters needed for successful completion of the task (i.e. parameters not directly related to the motion of the task but in-between translations, etc)

Interesting cs1-007 feels that the robot is only useful on an academic setting but not in real life, opposite to the rest of the Cs1 participants who noted amongst the benefits of using the robot arm for design its scalability and application on a construction setting.

Noting that working with a robot changes how you relate to the material to a situation where it doesn't depend on the ability of your hands anymore but in your capability to think of the design and program the machine properly. A very interesting comment by cs1-008 who intellectualizes the design problem through the use of the robot

Cs1-009 notes that some command which are very simple and easy to specify for the robot like the spinning yields impressive results that are somehow unexpected or not possible to think from the beginning / without the robot (i.e. this will be difficult to achieve with a different machine/ code)

Participants get concerned about how the robot will know where to go next. Although this is clarified with digital examples and explanations of the procedure it seems a robotic thinking problem. How will the robot know where to go, and his moves? Janette Vertesi in his book 'Seeing like a Rover' talks about how the closer humans work with robots they start to explain their movements and to talk as if they were the robots. the opposite of antromorphism. This confirms that on entry level understanding how the robot will know where to go next and how will it move can result confusing, but as participants get more comfortable with the robot arm, they start to express themselves in terms of the robot and to move themselves accordingly.

Robot Elements

This section is thinking about other objects or actants that form part of the robot but that might have represented a challenge and muddled or have gotten on the way of the participants working with the robot

04/02/2019 18:24:56

The code and software (Cs2-002)

The robot axis limits and joint rotations limits that mean things have to be flipped or the pattern set in a different way so that the robot reaches all the points without winding.

The limitations and winding / unwinding process forces the designer to rethink the approach to fabrication and even to the design (compare with surveys from Brazil) this might be why a lot of participants struggled a lot coming to terms with these limits.

The dead man switch is annoying as the robot might break hard when the participant is moving it trying to do a path due a pressure change that was not intentional.

Maybe also related to the mental model they have of the robot? i.e. the robot as a machine of endless possibilities and suddenly they find the limitations.

05/02/2019 11:01:26

Enjoys jogging and moving the robot, dislikes the coding and programming that have to be done before (Cs2-003)

05/02/2019 14:02:26

Cs2 -004

Dead man switch prompting the robot to stop due to a pressure variation due to the participant being engaged in massaging / modifying its design. Understanding how the coding and making of the robot path works can be difficult or time consuming.

07/02/2019 12:05:07

The software to design the robot path keeps coming as one of the things that participants found the most difficult. I would argue that without a preconceived design if they were to be just jogging the robot it might have been easier and fun but what is the point? and how would that be useful as a designer?

Participant noting about the simulation, she talks about doing more physical tests using the robot rather than relying on the simulation so much. The digital parameters in this case were off.

Participants CS2-009, CS2- 012, CS2-013, 014, 016, 028 are able to differentiate between the problems found on the end effector and the problems with the robot as a tool on its own, which is very interesting

The cage is an element that the participants feel detaches them from the robot experience. Whereas the cage is seen under a negative light, the safety button is a recurrent feature that made the participants trust the robot and feel safe about their interactions with it.

The table also becomes an issue for the later groups as there was enough concrete accumulated on it to cause problems.

08/02/2019 15:37:18

The code and software platforms as much as they are limiting objects for some, they are also source of excitement for learning new things and testing new workflows for others.

The directions and coaching give a sense of safety to the participants and encourages them to work with the arm. Initially as with the other machines, guidance and coaching encourage trust.

08/02/2019 22:03:37

Participant 010, this is the third time that not knowing where the robot is going comes as a factor that affects collaboration. **A face**, or some kind of laser that gives you an idea of where it is going to move to would be desirable.

10/02/2019 17:47:19

Although there is a sentiment of trust int eh robot and its movements, a recurrent feeling is that it would be better if it had sensors or could be aware of its surroundings (i.e., if it could know that the participant is there doing the task, including when someone else is jogging it.

Cs1-007 noting that 'speaking the robot's language would have made the process easier and more natural'

Access to a robot arm keeps being noted as an issue to develop more iterations, or learn more. Participants will tend to use a 3d printer, laser cutter, etc just because the ease to find.

External Things that Bothered the Participants

05/02/2019 10:10:23

CS2 -002 (Nik) was very fussed about how the robot reaches the limits and very fussed about the winding and having to return it to home position or move it in the other direction. She spends most of the interview talking about this. I should try to find why this was bothering her so much on the videos and field notes.

06/02/2019 13:04:17

The cage and the key that has to be used every time to go inside the cage do interrupt the flow of the exercise, especially as the university has a dual mechanism which means more steps to open and close. This was noted by many participants.

08/02/2019 07:46:26

Participants get a feeling that the school would not allow them to use the robot ever if it wasn't for this exercise. Some of them attribute it to the school being worried, the more machines they use the more responsibilities the school has. This idea of treating the robot like a 'precious' machine very different from the 3d printers, laser cutters is a problematic one, I would argue places a barrier from the very beginning and increases the preconceptions of a dangerous/ complicated tool rather than a useful tool.

Benefits of the Robot Arm

Thinking about what novel approaches to the design process can robots offer to designers, or what unexpected insights they are giving.

04/02/2019 13:05:33

The robot doesn't have any preconceptions about the material or sensibility so it won't be worried to push harder or to go beyond the limits of the material, whereas the designer might limit himself because he is afraid of it breaking, tearing, etc. he won't explore the limits or so many different conditions as the robot could.

04/02/2019 13:22:27

They offer the designer distance from the design, allowing for different perspectives of the same to come to light and hence new ideas can form on the designer head from of these unexpected views.

The robot can also offer more details than what the naked eye perceives and these can inform further design decisions, it can improve /enhance the designer perceptions by giving more detailed or unexpected information (views that the participant couldn't see, etc).

The robot allows to see the material behaviour in a more quantitative way.

06/02/2019 12:21:24

Feedback is the best thing about the robot, allows to see the variations between your digital explorations and what happens in the real world. It gives you an idea from which you can then investigate further what are the reasons for what is happening.

07/02/2019 15:15:29

The limitations of the robot (machine) are useful to push the way you think. Participant compares it with the way she has learned the limitations of her hands, once she learns the limitations of the robot, she can use it to push her design process (Cs2-012).

08/02/2019 07:44:51

Without the design of an end effector it cannot do anything which is a problem meaning they cannot start using it straight away, but it also implies that there are multiple possibilities and uses for it.

08/02/2019 10:48:35

It only needs to be setup once, after this it can do the work precisely, reliably and repeatedly (this participant is interested in doing a prefab project). This is a good point, as it has only been reflected by one participant before that there are struggles in learning how to work with it or in setting it up once you learn the possibilities expand considerably. It is a one-time investment, different from other fabrication machines that might also need to be learned but then they can only do one thing. The idea of setting it up is not so relevant to this research as robots are well known for its reliability and workability in the production line, the aim here is related to creative tasks where repeatability is not needed.

08/02/2019 15:42:34

Accuracy, although something that is known from robot manipulators, for people fresh to the field, they find impressive that the robot was accurate in doing the tasks. A possible explanation for this is the anthropomorphism that we tend to give to robot’s vs other machines.

08/02/2019 21:59:22

The robot can give you more control of the form. In this affirmation it seems that parametric models allow a kind of uncontrolled freedom as they remove all the physical constraints from the model. Getting back some of the physical constraints - which the robot does- would give back control. This is a very good point.

Participants that have done form finding exercises physically might find a similar problem, after moving all the points they can lose track of what things end where. The robot can give them back this accuracy and control over their deformations.

19/02/2019 11:09:09

Noting that designing with robot arms is not only a change in the tool but in the design space of possibilities that the tool offers. A very important point noted by a mature student is how the robot can give more control to the designer in downstream stages of the design process. In this scenario, the designer would know how the construction process could work and have a stronger opinion on the material and works as he has tested it with the robot.

Scalability of the process done by the robot is noted as a positive feature of a robotic based design exploration.

Noting that robot arms can close the gap between architects and the builders in the construction site. They have the potential to place architects on control of the construction process.

Reactions to Robot Arms

Recording participants responses to robot arms. When I first saw one, I was also...

Thinking about gender and the robot arm and initial reactions.

Do robot arms have genders???

04/02/2019 13:42:18

Is better for robots to not have any gender: Professor Tatsuya Nomura, who has spent decades studying about the difference between a man and the machine concludes that the more significant problems are not the debate between making robots look human or not. It is between referring to robots as 'him or her'. The assignment of gender between robots is a very controversial issue because the gender in robots may reproduce gender stereotypes in the current society (i.e. robot females made to be receptionists, etc).

04/02/2019 14:16:01

Cool.

Exciting.

Like a new toy.

Fun.

06/02/2019 13:16:47

Heavy.

07/02/2019 16:11:30

Adorable

I love talking to him.

08/02/2019 13:01:54

Interesting.

08/02/2019 15:31:44

Participants feel excited to use the robot arm, they see it as a unique opportunity and a common comment is that the machine is generally locked behind a cage and a door. When they pass by the room is only a little window through which they can see the machine that lives inside. A feeling of inaccessibility or a forbidden world. When they see it coming alive it gives them pleasure and excitement to use this machine.

Feeling of power when they jog the robot to do something that they want, and they accomplish the task. Apparently, this is making them feel powerful. Participants feel It's unbelievable that the robot did what they told it. This again, can be due to media representations of robots and AI that misguide the perception of them

11/02/2019 10:43:37

How do people engage and conceptualise robot arms? Are their reactions very different compared to mine?   Am I losing the voice and experience of the participants? How does the robot arm view the participants???

Noting the excitement not only because of using a robot but using it for design.

APPENDIX M INTERVIEW SCHEDULE FOR INITIAL EXPLORATIONS

Name: ________________________ Nationality: ____________________

Profession: _____________________

1. Which year are you currently studying or when did you graduated from design school:

2. What are the tools that you normally use to design?

3. Is it common for you to make physical models of your projects?

4. Can you recall your initial reaction to the robots when you saw them? The first word that came to your mind.

5. When you started the workshop, did you have many challenges in your professional or academic life that got you interested in digital design and fabrication techniques?

6. Materiality as defined by Antoine Picon doesn't refer to the material or matter but to the relationship that humans form with materials and matter. Materiality is a co-construct between human and matter. Did you feel the use of the robotic arm enhanced your relationship with materials?

7. Did you feel the robot characteristics (speed, movement, limits, etc) were important during your design process? Did you change any design aspect because of them?

8. How will you describe your relationship with the industrial robotic manipulator?

9. Was working on a team helpful? How did you interact and share the experience with your team?

10. Were there times when you felt like you needed to negotiate with your team?

11. What do you think an industrial robotic manipulator can add to your design process? How can it be useful?

12. Were there times when you felt like you needed to negotiate with the robot?
13. What would have helped you to integrate the robot to your design process during the workshop?

14. What name will you give to the robot?

15. Which machine of the 3 used during the workshop for digital fabrication (laser cutter, 3D printer, robot) you feel more likely to use in your professional life? And why?

16. Do you have any suggestions or further comments about design strategies when using robots?

APPENDIX N MACHINE LEARNING EXPLORATIONS

Introduction

Robots and more specifically robotic arms are increasingly being explored beyond fabrication machines as design tools capable of augmenting and extending the designer solution space into the fabrication and material manipulation stages. Recent approaches try to embed craft knowledge into the robot for its path planning decisions. These include the analysis of actions such as those from a carpenter for wood carving (Brugnaro 2017) or from a stonemason (Steinhagen et al. 2016). Common among these projects is the idea of establishing a direct link between physical material manipulation tools and machine intelligence by training the machine to replicate and eventually augment the actions of the human.

The work presented here was carried out with the intention to start testing how the robot can become a collaborator to the human designer through the design process by training it in the use of novel materials that enable formative design processes. This section explores the potential of deep learning to augment architectural design processes through establishing a link between the phase changing of the material and the working coordinates of the robotic manipulator shaping the material. The same phase-changing 'concrete canvas' material is used for its non-linear behaviour and because it offers opportunities for the material, the robot and the designer to interact and combine their agencies at the phase-changing step before a final result is achieved.

In the context of this dissertation and based on the qualitative and quantitative data, machine learning is explored as a tool to enable the robot to have more information to support participants decisions. By correctly anticipating the material deformation given any set of plunging coordinates, the robot can then provide the participant with valuable additional information. Other geometry and structural analysis tools could be incorporated at this step to enable designers to take informed decision. A database of the material deformations given different robot plunging coordinates was created and recorder, the data was then cleaned and labelled in order to train a deep neural network. The application of the trained neural network to predict material deformation results based in robotic coordinates has been successful. However, its application with design participants requires from a highly specific setup to allow a smooth designer-robot communication of the predicted results. More work to refine the interface in order to test a HIRC design scenario enable by deep learning is currently being done by the researcher and out of the context of this dissertation.

Setting the Research Experiment

The experiment setup includes an ABB 6700 robotic arm fitted with a dual head end effector for cutting and plunging the concrete material. A realSense sr300 scanning device used to collect the deformation data, and a material called Concrete Canvas, which is made of a layered composite matrix with a cement mix in its core that allows repeated plastic deformation. The 3D model was derived using a physics engine that simulates the behaviour of the concrete fabric material. Incisions with different patterns were then inserted into the model, and its deformation was then observed. The resulting data were then moved to the robot that was used to both cut the patterns into the material and iteratively deform it during the curing process. The first stage of the training method focuses on capturing, with the scanning device, a series of deformation sequences derived from the robot plunging and hydrating the concrete cloth.

Material, Surface Definition and Pattern Generation

The same concrete canvas material was used as described in section 7.5.2. The design process for the surface definition and pattern generation have been described in sections 7.5.2.1 and 7.5.2.2

Robotic Tooling

Four main factors influence the final shape that the concrete would take: 1) pattern of cuts and joints; 2) plunging positions; 3) plunging depth; 4) concrete hydration. The hydration of the concrete was identified as a variable of the formation process that was not controlled by previous iterations of this research (Vazquez & Jabi 2017a; Vazquez & Jabi 2017b). It is crucial for the neural network to learn how the concrete behaves throughout the formation process and have access to the different variables that influence its formation.

A robot end effector with two heads, each at a 45-degree angle from the centre was designed. On one head, the robot has a pivoting knife that allows it to cut the pattern of cuts and joints into the material, even when the material is hanging (Figure N-1). On the other side of the head, it holds a pressurised water sprayer that ends on a sphere with multiple holes (Figure N-2). At each plunging position, the sphere does a 360-degree rotation to 'massage' the concrete while spraying water around it. The hydration step is then controlled. Additonally, the amount of water that is covering each area during the plunge can be modified by reducing the length of the spraying time. A point cloud is recorded during, and after the plunge, the effect of the water over the concrete becomes evident on the bounce back that the concrete presents on the resultant point cloud.

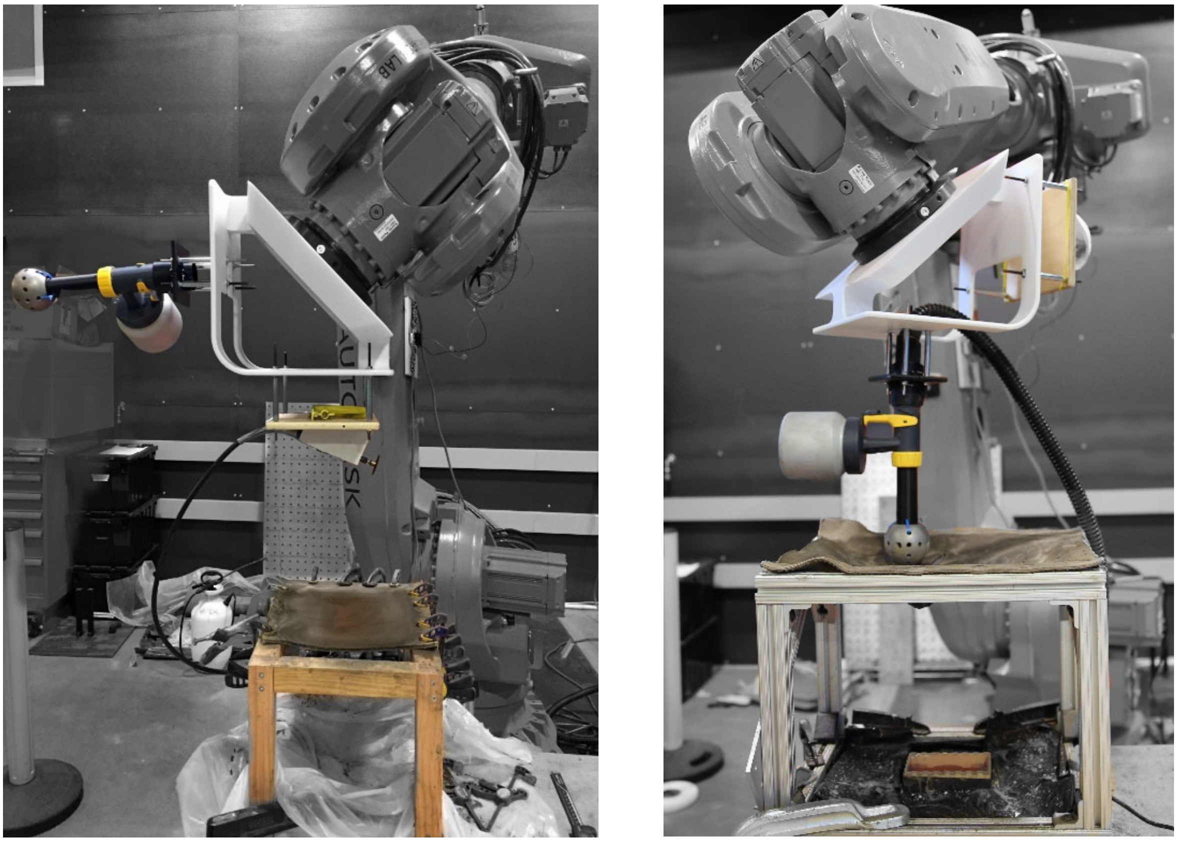
Figure N-0-1 Pivoting knife for cutting the concrete cloth both hanging or on top of a table.

Figure N-0-2 Rotating and hydrating sphere on the opposite side of the end effector

Sphere Calibration and Data Collection

A setup for data collection was designed so that all the point clouds on the data set are collected with the same origin position to reduce the amount of image processing to be done after collection. The setup consisted of a 500w x 600d x 400h mm aluminium frame where the concrete cloth is stretched and hung for cutting and plunging. Situated at the bottom of the frame and centred to it an intel RealSense SR300 scanning device inside a water protective case (Figure N-3).

Figure N-0-3 Data Collection initial set-up. End effector with cutting tool on one side and plunging and hydrating tool on the other side. The concrete cloth is tightened to the wooden frame for the whole formation process. The scanning device is below at the centre of the frame. Left: setup 01 Dremel cutting device. Right: set up 02 Swivel blade as a cutting device



Before each iteration of cutting and plunging five sphere positions are recorded: one at the centre of the frame and one inside each of the corners to calibrate the point clouds with the robot coordinates and offset any displacements that might have occurred during the setup or previous plunges. The origin of the robot coordinates is always relative to the frame, and the origin of the sensing device is calibrated to be at the centre of the frame.

After the calibration positions are taken a piece of concrete cloth is positioned and tightened to the top face of the frame. The pattern of cuts and joints previously defined and simulated is cut by the robot on the cloth, and a first scan of the cloth condition without plunging is taken (Figure N-4 and N-5). A series of 100 randomly generated points -inside the frame boundary- are then converted into robot plunging coordinates. The z-value of the random points goes from 0 at surface level to a maximum of -120mm to avoid tearing the concrete cloth during the plunging. The robot goes through each of the plunging positions, at each position it does a 360-degree rotation of the sphere to ‘massage’ the cloth into shape.

The pressurised water gets activated when the robot touches the cloth, so that as the sphere rotates the concrete gets hydrated on the same location.

One scan is recorded during the plunge and one after the plunge. The second scan subsequently becomes the initial cloth condition for the next plunge. The sequence keeps repeating until all the robot has gone through all the plunging positions.

A total of 3000 points clouds where collected across ten different concrete pieces - 1500 plunges and 1500 resultant conditions. The pattern of cuts and joints was kept constant in these ten pieces in an attempt to reduce the number of variables and test the strength of the system to predict the material outcome correctly.

Figure N-0-4 Concrete pieces from the training data set. The initial pattern is the same for all, the plunging and hydrating coordinates are randomly generated for each of them.

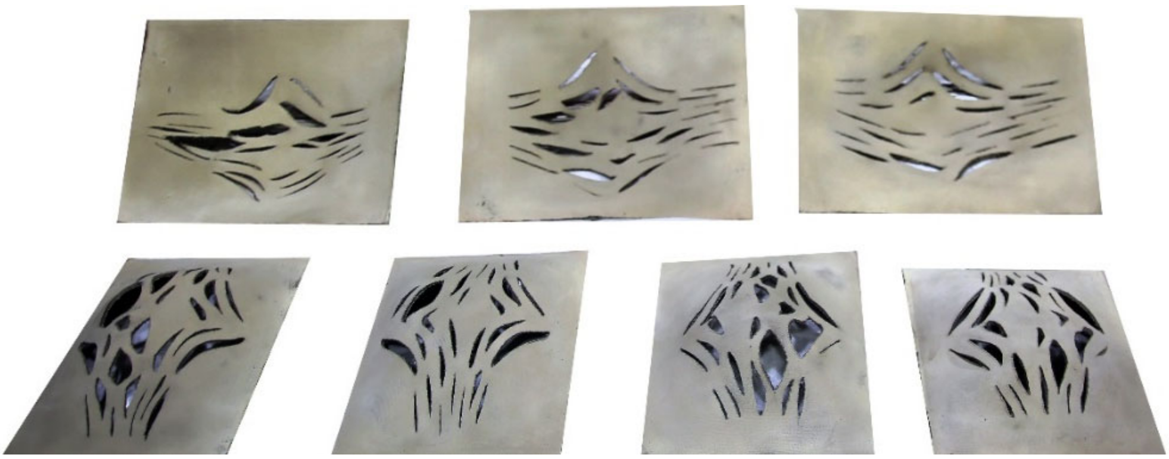


Figure N-0-5 Back view, differences in the 3D pop-up pattern due to the plunging and hydrating sequence.

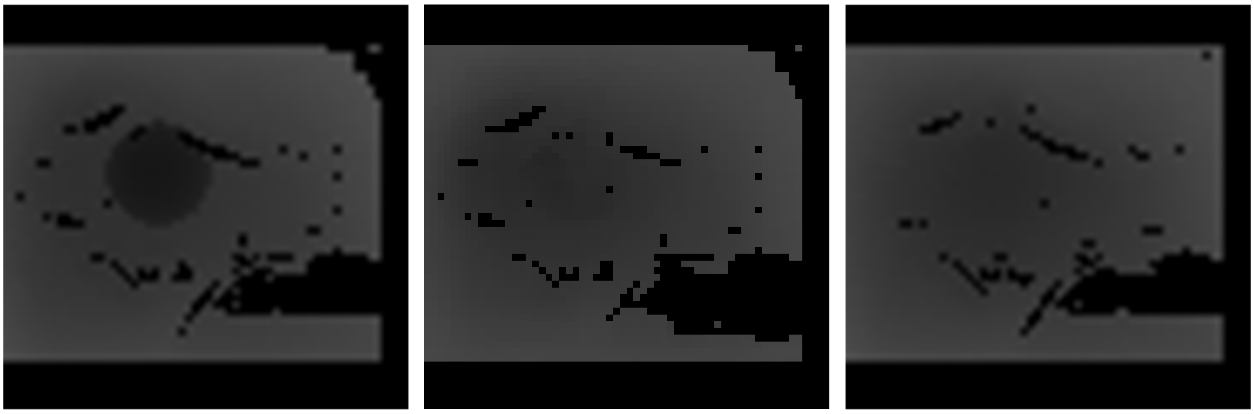
Data Preparation and Neural Network Training

Point clouds captured during the concrete deformation process were converted into depth images. Depth images contain the same amount of information needed for the network to understand the material deformation at a lower computational cost. Initial 640 x 480 pixels images were reduced to 480 x 480 to crop the frame and additional information surrounding the concrete cloth. These images where then further reduced to 240 x 240 pixels. From these images, each 3rd pixel is selected for a final training data set of 3000 images at 80 x 80 pixels each from the different concrete cloth deformations.

An additional set of images was generated containing only the coordinates of the sphere and a radius around it corresponding to the sphere dimensions. The images of the sphere positions were then overlapped to the images of the concrete resultant deformation (Figure N-6). Overlapping two images is a technique commonly used for machine learning studies of bridge structures: over-positioning the location of the acting loads to the collected images of bridge deformation (Gonzalez et al. 2017; Neves et al. 2018). The technique was used to ensure and accurate mapping of the plunging location and its resultant shape. A blur of 20 was applied to the set of overlapped images to reduce the noise.

A U-Net deep convolutional network architecture on TensorFlow was used as described by (Ronneberger et al. 2015). This method allows to effectively train a neural network using less annotated images by augmenting the data set relatively to traditional network training strategies. In this method, the contracting and the expansive path are more or less symmetric. Hence, a larger number of convolutional layers is preferred to keep a large number of feature samples. The image dataset was trained using 40 feature layers on a 5 GPU core processor over 12 hours.

Figure N-0-6 Example of input images from the training data set. Left: Input Image showing the initial condition with the sphere overlap; Middle: actual cloth condition after plunging; Right: Neural Network guess of the resultant shape after plunging.



Data Analysis and Validation

The evaluation of the training process is performed through a validation data set of 10 images - 5 pairs of plunging and resultant condition- which were reserved unseen to the network and used to test its prediction rate. From this dataset four predictions from the trained neural network resulted correct and corresponding to the results from the dataset.

Finally, two physical tests were performed with new pieces of concrete cloth. These pieces had the same pattern from the training data set cut by the robot. They were deformed using 120 randomly generated x, y, z positions and a scan was taken. This initial condition scan was then paired with their corresponding randomly generated x, y, z plunging position for the sphere (Figure N-7). The results were scanned to be compared with the predictions of the trained neural network. In both cases, the trained network, successfully predicted the resultant concrete shape, including the deformation after plunging when the concrete springs back to place, within a 5mm range (Figure N-8 and N-9).

Figure N-0-7 Physical test performed for data validation. Input image of a cloth existing condition with an overlap of the proposed plunging position.

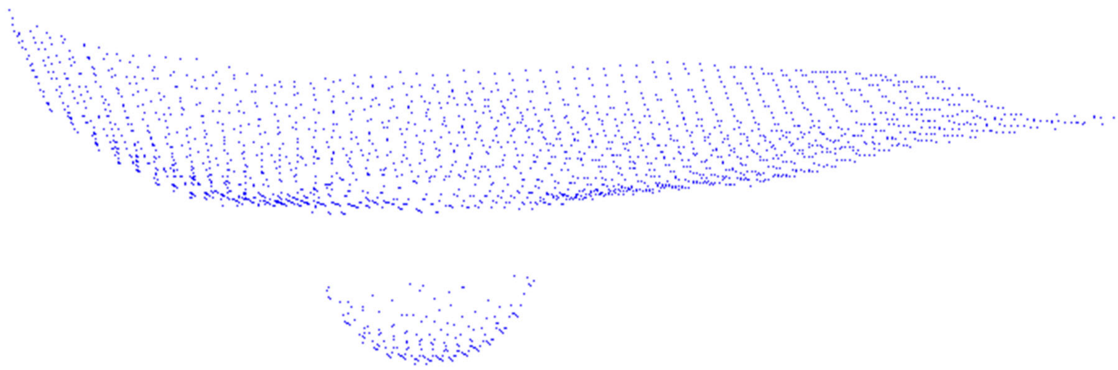
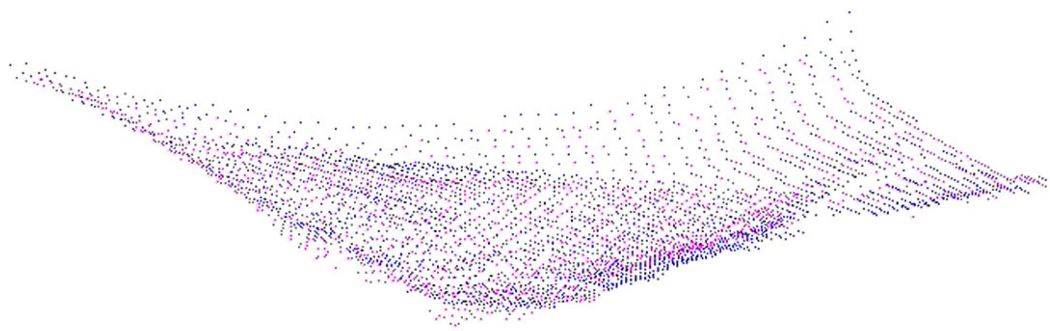


Figure N-0-8 Comparison between the neural network predicted result (blue) and the actual result after performing the plunge and scanning (red). Top, centre and bottom.



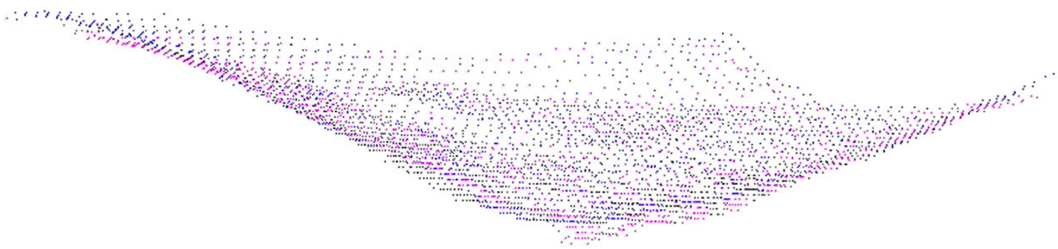


Figure N-0-9 Top and Bottom: Images of validation shell (flipped 180 degrees after formation process)

Conclusion and Future Scope

Deep learning research in robotics has been geared towards automation of human. In this section, the proposal is to use u-net convolutional neural networks as a tool to couple material deformation with robotic motion to enable the robot to become a collaborator or advisor to the designer through the design process. The robot, in this scenario, can offer resultant geometries given different plunging positions for the designer to choose before proceeding. The robot, enabled by its computational power offers a bigger picture of possibilities for the designer to choose at each iteration. The robot through the material acquires agency becoming a co-designer in the design process rather than remaining as a final fabrication machine.

The research presented in this section shows that deep learning can be used as a successful tool to merge material deformation with robotic fabrication. This research also illustrates that machine learning can be an efficient tool to predict material deformations for non-linear materials where the physics are not known. The trained neural network demonstrated the feasibility of capturing tacit material knowledge into a robotic system, i.e. the trained system successfully addresses changes in the material such as the bouncing back of the concrete after a plunge and hydrating iteration. It is important to note that the depth of the plunge is not equal to the depth of the deformed cloth as the fabric will bounce back and local deformations have implications in the overall cloth. The neural network evolves new material possibilities as the design and fabrication process unfolds by learning to form the new results at each iteration. However, there are fundamental differences between the input - output learnings of geometric deformations that deep-learning models do, and the way humans think an learn. The participants on this exercise could understand the potential deformations of the cloth and the impact of the initial design pattern as well as of the robot plunging positions from embodied experience instead of having to be presented with explicit training examples.

Two divergent trajectories are foreseen as a next step for this section in which different strategies are applied to the use of machine learning for the design process:

1) Further develop and utilise the current network data set to find the best set of parameters for a physics engine driving the simulation of the resultant concrete shapes. In this scenario, data will be collected from the simulation stage to record which parameters are driving each formation. The parameters from the physics solver will then be pushed through the network. The current data of real material deformations will also be pushed through the said network as examples of different inputs and their resultant deformations. The aim is for the neural network to learn which parameters of the physics

solver can be used to approximate the concrete deformation better. The rationale is that it will be faster for a designer to predict a deformation using a physics solver than going through the neural network prediction workflow.

2) Develop a more intuitive interface that could be used by non-expert users during the material formation process. This platform would integrate design intention and goal with the material explorations - mediated by the robot-. The proposed interface would also allow the designer access to different layers of information, besides the resultant deformation, i.e. FEA analysis of the potential deformation for different plunges in specific coordinates. This will allow the designer to make informed decisions relative to different material and structural variables throughout the material formation process. TensoRt is being explored as the platform for such interface as it allows ease of access to the trained neural network. In this scenario, a scan of the existent, deformed concrete shape can be taken, uploaded to Tensors and intuitively pushed through the trained network to get the resultant deformation in a user-friendly way. The developed platform would then be tested with different users to understand how the robot can become a partner in the design process.

On the current state of the research machine learning was used as a tool to link the material behaviour with the robot motion so that the robot can have enough information at each iteration to inform the participant. The human and the robot can become creative partners where they support each other. However, it is important to consider that the design process is a creative task. Creativity is a value that humans add to things (I.e. robots would not have a sense of what is creative). The machine might be doing a ‘creative’ novel move but it won’t know nor care that it is solving the problem in a particular creative way. HIRC in the design task requires from a joint effort between the man and the machine.