A Collaborative Approach to Digital Fabrication: A Case Study for the Design and Production of Concrete 'Pop-up' Structures

Alicia Nahmad Vazquez and Wassim Jabi

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The research presented in this paper utilizes industrial robotic arms and new material technologies to model and explore a prototypical workflow for on-site robotic collaboration based on feedback loops. This workflow will ultimately allow for the construction of customized, free-form, on-site concrete structures without the need for complex formwork. The paper starts with an explanation of the relevance of collaborative robotics through history in the industry and in architecture. An argument is put forward for the need to move towards the development of collaborative processes based on feedback loops amongst the designer, the robot and the material, where they all inform each other continuously. This kind of process, with different degrees of autonomy and agency for each actor, is necessary for on-site deployment of robots. A test scenario is described using an innovative material named concrete canvas that exhibits hybrid soft fabric and rigid thin-shell tectonics. This research project illustrates the benefits of integrating information-embedded materials, mass-customization and feedback loops. Geometry scanning, parametric perforation pattern control, computational analysis and simulation, and robotic fabrication were integrated within a digital fabrication deployment scenario. The paper concludes with a detailed report of research findings and an outline for future work.

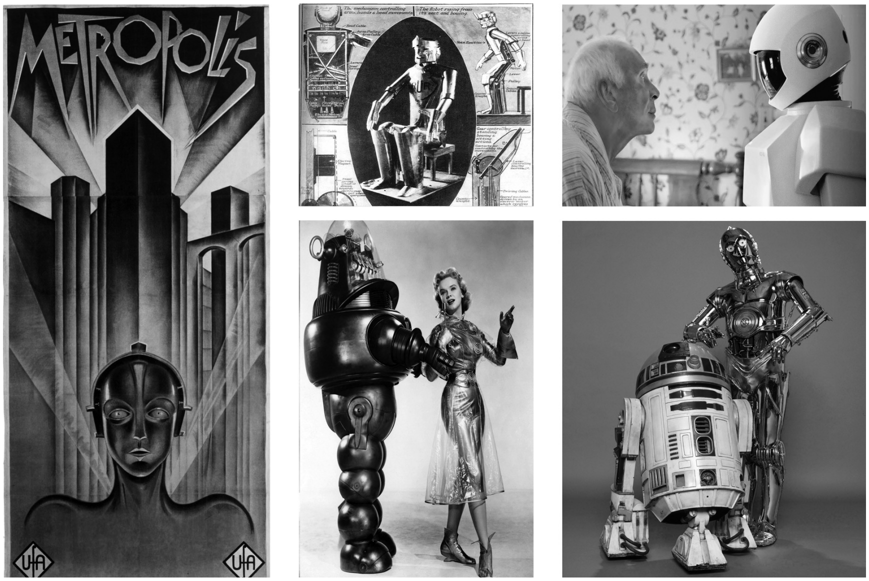
1. INTRODUCTION

Research on robots for architecture and the construction industry is not recent. A range of interesting and compelling studies to automate and introduce them into the construction workflow has been documented since the 1970's, especially in Japan [1]. Most of the efforts then were directed initially towards methods for construction automation through prefabrication, with certain degrees of ability for customization. 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[2]. What is new, in this era of robotics in architecture, is their ubiquitous presence in all areas of the urban landscape, a greater computational literacy within the architecture discipline, more powerful and distributed computing capabilities and less expensive and smaller electronics that have allowed for more accessible sensors and 3D scanning methods. These conditions have made connecting the physical and the digital easier and more available. In combination with new material technologies, robotics in architecture is positioned as a strong force that although arriving from outside the traditional environment of robotic evolution, is breaking constraints and opening new vistas. A symbiotic relationship between architecture and robotics is being formed where they push each other's outer boundaries to investigate and create new modes of practice using advanced technologies.

Concrete canvas is a new material technology that embeds cement within a flexible fabric matrix that, when hydrated, transforms into a rigid concrete shell [45]. We use the term Pop-up concrete to refer to a workflow that we have designed that is composed of three general steps: 1) the robot superimposes a cut pattern on flat sheets of concrete canvas, 2) the canvas is popped-up using an inflatable structure underneath it, and 3) the inflated structure is hydrated to achieve a rigid structure. The design-to-fabrication workflow of on-site pop-up concrete structures presents an innovative shift from the current trends of automated robotic fabrication in architecture. It explores and experiments with the potential of a human-robot collaborative process and new materials that depart from the traditions of the pre-robotic construction era. These allow for new tectonics and material sensibilities to emerge as a product of digital fabrication tools, structural analysis and material and human agency in a continuous and iterative sensor-based feedback loop. Within this research, we aim to provide an option for the quick deployment of mass-customized pop-up concrete shell structures using a design process that is responsive and adjustable not only during the digital design phase but also during its materialization.

2. ROBOTS: A DISCIPLINE WITH A HISTORIC CARTESIAN DIVISION

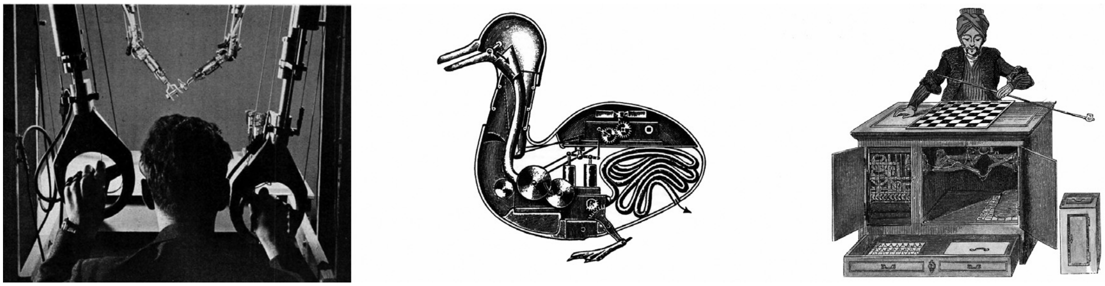
Robots have always intrigued humans; they have been featured in plays, books, cartoons and films and captured our imagination especially after the



◀ Figure 1. Left: Metropolis Poster [32]. Middle top: RUR [33]. Middle Bottom: Forbidden Planet movie poster [34]. Right Bottom: Star Wars [35]. Right Top: Robot & Frank [36].

1960s, an era of great technological progress and great 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, 'Robie' in the Forbidden Planet 1956, etc) (Figure 1). Robots are usually depicted as creatures in the mould of a human who is under the control of its creator. The original Star Wars from 1977 brought the 2 most famous fiction robots R2-D2 and C-3PO (Figure 1). They are amazingly intelligent, able to hold full conversations with people, execute difficult engineering tasks that need not only mechanical strength but also brainpower. It is only more recently with the movie Robot & Frank (Figure 1) that a more plausible scenario is shown, one where the main character is assisted by a robot who 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 do tasks together [3].

The concept of a robot has advanced and moved from sci-fi into reality, particularly in the last 50-100 years. 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"[4]. However, the Czech Capek only coined the word "robot" in 1928 and it means 'slave or worker'. He used it for his play RUR "Rossum's Universal Robots" (Figure 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 [5]. This became more evident in 1951 at



► Figure 2. Left: Master slave manipulators, MSM-8 [37]. Middle: Vaucanson's mechanical duck [38]. Right: An engraving of the Turk [39].

the Argonne National Laboratory where the necessity to manipulate dangerous radioactive materials led scientists to develop a system for 'tele-operation manipulation'. A set of 'slave' arms (Figure 2) 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 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 [3].

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

A very early example of the desire for a human–robot collaboration was the Turk (Figure 2), a chess player that was a mechanical humanoid, designed and built by Wolfgang von Kempelen in the late eighteenth century [6]. 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; 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 as the first intent of blurring the divide between the body and the mind of the machine an idea that still pervades in modern day robots, and of building an autonomous robotic device capable of interacting and responding to the human mind [7]. 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 the Jacquard's loom. Similarly, during this time Babbage developed a general-purpose machine which input was controlled by punching cards. This was the beginning of computer development and subsequently of robotics.

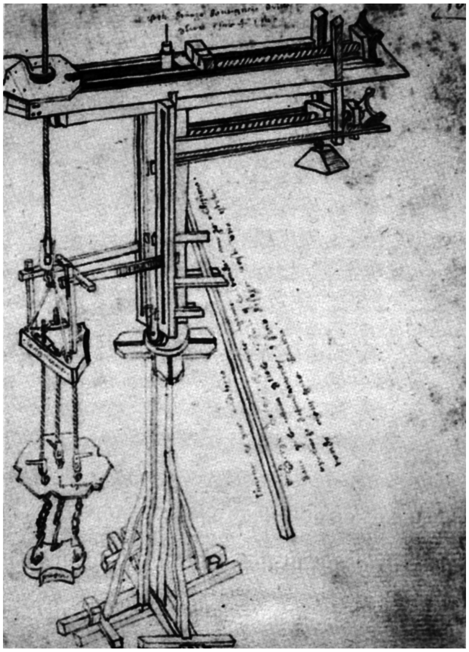
Aside from many romantic perceptions, "robots are first and foremost computers" [8]. The limits of what is and what isn't a robot haven't been agreed, thus creating an on-going debate amongst scientists. Definitions range from the very general inclusive ones to the very complicated and highly specific. The Oxford dictionary 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, 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." [9]. However, the preferred definition in the context of this paper is the one from roboticist Peter Corke who writes "a robot is a computer that can do things in the physical world" [3]. The requirement of interactivity and feedback with the physical world and its actors is a key idea and motivation for this research. Within the context of architecture, robots can be the ideal link between the physical reality and the digital world that we have created.

There are many forms of robots as have been classified in [10] that are being developed with great potential uses in architecture. For the context of this paper "robot" refers to an industrial robotic arm. The robotic arm has been in use in the industry for over 50 years. It is a proven multipurpose, safe and reliable technology that can be adapted to work with different materials and in different ways through custom designed and built end-effectors [11]. The robotic arm gives us a well-established basis to re-use and adapt within our digital design and fabrication workflow. Although architecture is the main focus of this paper, including a general introduction to robotics and assessing within a wider context provides us with insights to our argument for a robotic collaboration that is not currently visible.

3. ARCHITECTURE: A RECENT CARTESIAN DIVISION

Similar to robotics, architecture has had a Cartesian division between intellectual work and manual production. During Brunelleschi's and Alberti's period, two kinds of models were established: one that abstracts architecture from construction and moves it away from the construction site; and an opposing one where the architect spends time building and designing "not only the Florence Duomo but also all the tools necessary to construct it" [12]. There is a certain tension between these two ways of thinking. While architects are not usually builders, can the designer be completely isolated from the problem of building? The current fascination with robots and robotic processes suggest that this isolation is not possible [13]. It indicates a desire to regain control over the fabrication process, in a

► Figure 3. View of Brunelleschi's revolving crane by Bonaccorso Ghiberti [40]



more holistic approach where technical invention allows the architect to push the limits of design.

The problem of building and the use of robots in construction is no longer a mechanical problem as the one Brunelleschi had when he built the dome of Florence: lifting big slabs, big volumes of stone for which he created specialized jigs and lifts. Nowadays, the mechanical machinery is readily available. Digital fabrication has resulted in the development of different workflows that directly connect designs and their realization escaping from an industry that has thrived through standardization. Robotic manufacturing then becomes an intellectual problem that takes place within the architects' terrain [13].

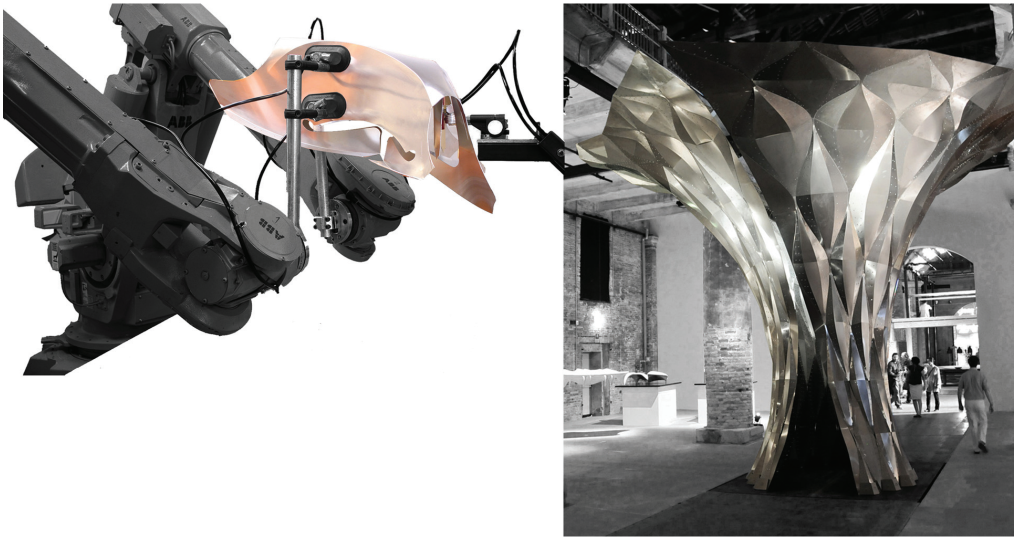
4. ROBOTS IN ARCHITECTURE

While research in robotics in architecture has matured it still faces several key challenges as we enter this new stage. Firstly, the uni-directional flow of information that exists from design model to code to robot [1] represents a segmented sequence of geometric rationalization to data translation. Secondly, questions and scepticism have emerged surrounding the use of digital technologies that produce pseudo-complex surfaces which cannot be modelled or fabricated manually and are not a real architectural solution [14].

If robots are going to re-enter the construction site, we need to identify when and when not to use them. In most cases, the automated portion of the construction process is only a fraction of the overall work necessary to complete any building. Therefore, it is important to consider how it fits into the process and whereas it will create unnecessary complexity as to become difficult to manage downstream. While new processes are exciting and the possibilities are immense, they shouldn't be considered in isolation. In some of the projects, the manual assembly part is as complicated if not more so than the part constructed by robots [15]. We need to consider a holistic approach to construction methods that successfully incorporate robots, humans and material agencies on-site.

Nascent technologies usually start by mimicking processes followed by their preceding technologies, (e.g., the first musical instruments were made to replicate the sounds of nature). Once the technology matures it starts to understand the constraints and thus abstract and reinterpret the problem to finally create its own language [5]. The use of robotic arms in architecture is reaching that stage. 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 also starting to accept and incorporate the language of the robot in their creations. The Venice Biennale entry in 2012 'Arum' (Figure 4) from RoboFold and Zaha Hadid Architects is one example of this kind of collaboration. An existing metal folding technique was robotized 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 pushing it and developing it further to arrive at a joint design solution that created a new aesthetic product of the machine and the designer [13], [16]. 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.

▼ Figure 4. Left: Robotic folding process [16]. Right: 'Arum', 2012 Venice Biennale [41]



4.1. Automation dreams

The ubiquitous presence of robots in architecture laboratories has been interpreted as a desire to automate the design-to-fabrication processes. We are witnessing a surge of plugins for CAD software that are starting to encapsulate the expertise required to assemble structures made out of large quantities of discrete components and automate construction, (e.g., *Scorpion,* a Rhino plugin for robotic laying bricks and mortar [17], and *BrickDesign,* a software tool also for bricks by ROB Technologies [18]). These are developments that not only automate but also allow design within the tool something not common to traditional robotic automation tools. The continuous development and prototyping of robotic brick-laying strategies makes them a great push towards real industrial robotic construction. However, they still remain constrained to the laboratory or to very controlled outdoor environments. This, together with the fact that robots are not adept at working in unpredictable environments [19], makes it tempting to consider them only for off-site prefabrication. However, the possibility of on-site application is appealing as it enables fabrication directly on-site with the modifications and changes needed over the course of a building process and eliminates the need of costly transportation of prefabricated elements. Nevertheless, this requires further research and the proper design of a collaborative on-site fabrication process.

▼ Figure 5. R-O-B by Gramazio & Kohler is a movable robotic unit that can work outdoors within fences in a very controlled environment [27]

5. TOWARDS A COLLABORATION

By 2017 there will be more than 2 million industrial robotic arms installed worldwide which means they will work closer to people [20]. 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 robots, generally pre-programmed to repeat a singular, precise task for all their robotic life, they are not expected to come up with any unexpected behaviours or any ideas of their own [21]. These robotic arms normally operate in controlled environments that have been purpose built for them. The construction site, in contrast, is unstructured, empty and lacking a purpose-built environment. For robots to survive on such a site, they need fabrication processes that allow them to communicate and work with each other and with humans. Additionally, differently to traditional settings, in architectural applications, robots are used for individualised fabrication. Even if they are performing the same task they will follow a different pattern during each iteration. 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"[22].

▼ Figure 6. Alexander McQueen 1999 'Savage Beauty', the final dress paint was an interaction between the robots' and model' movements and actions [42].

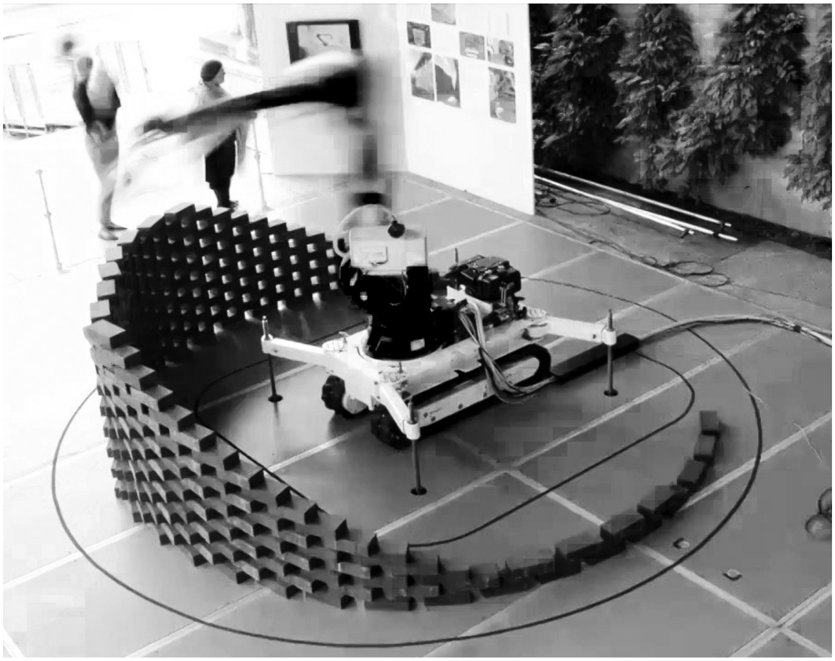
Humans and robots can establish meaningful collaborations where they can benefit from each other strengths and work as partners towards a common human objective. The most successful human–robot collaborations today are in underwater or space operations where robots have sensors and autonomy for some tasks but are also remotely controlled by humans in real time in what is called "tele-operation". The most flexible component of a manufacturing system is the human operator. After a race for full automation, the manufacturing industry has come to realize that "ensuring a meaningful involvement of people in decision–making and operation of manufacturing robots is critical to their success"[23]. The manufacturing industry is turning its attention to a more harmonized human–machine system. 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' [9]. We can then conclude that robots are more suitable for semi-autonomous or pre-programmed precise tasks while humans are more suitable for making judgement calls.

5.1. On-site collaborations

The fact that not two construction sites are alike and their dynamic nature where things are continuously growing and changing, has made it a difficult territory for robots to explore. Various attempts have been made to introduce autonomous, semi–autonomous and remote-controlled robots to the construction site with the purpose of automation [24]. The introduction of robots to the construction site faced two problems: first, differently from the manufacturing industry where the products are moving along a production line while the robot remains stationary, in the construction industry the building remains stationary while the robot has to be mobile [25]. Second, attempting to change the configuration of the construction site to make it 'robot friendly' highly underestimated the complexity created by the numerous parallel tasks that happen on a given construction site at any given point.

▼ Figure 7. Left: Kajima Corporation, Façade inspection robot, Tokyo 1988 [2]. Right: Shimizu Corporation, Concrete finishing robot, Japan 1987 [2].

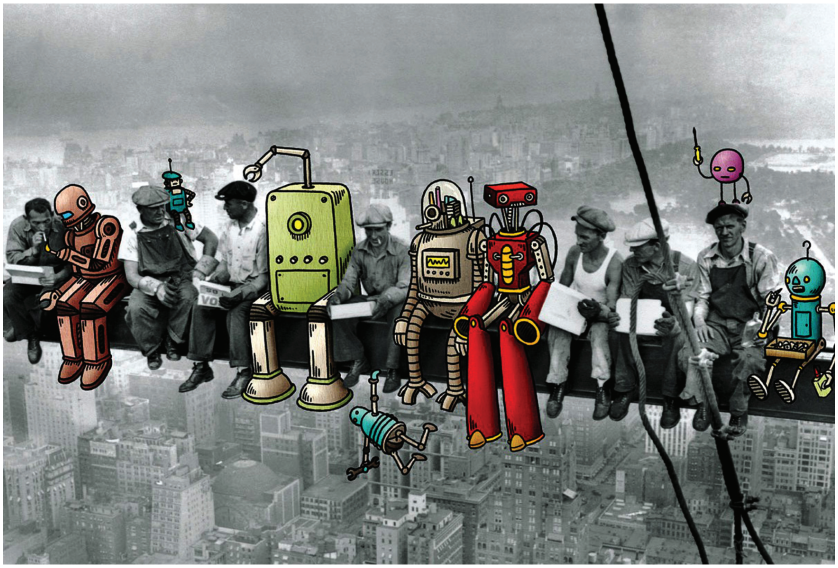
A more recent attempt is the 'Mobile Robotic Unit' (Figure 8) developed at the ETH Zurich, which is an industrial robot mounted on a mobile unit and outfitted with 3D scanning devices and sensors that continuously inform the robot allowing it to self-calibrate and perform mobile construction[24]. This approach has a lot of flexibility to be implemented on-site as the robot doesn't need any changes to the site itself and within a designed process it can interact with downstream and upstream non-automated or automated construction tasks. This flexibility allows it to be more compatible with the dynamic nature of a construction site.



◀ Figure 8. Gramazio and Kohler Mobile Fabrication Unit. [28]

Embedding sensors into the body of the robot changes its configuration and the possibilities for a real human partnership. They open up the dialogue where the robot has a certain degree of autonomy and it can make some decisions with the information from the sensors, but it is also able to communicate information back to its human partner for feedback rather than catastrophically failing. It allows the robot and the human to ask questions to each other and jointly solve a problem. The robot has the precision and the understanding of complex 3D digital geometries that it can translate on-site while the human sets the parameters and makes the design and structural decisions until the robot reaches the desired shape with the material. New connections between the machine, design process, code generation, fabrication, sensor-driven skills and human-machine interaction have to be designed. These connections are not sequential but need to incorporate several loops that affect subsequent outputs. This

► Figure 9. Image Andrew Rae. [43]



feedback loop with human-machine interaction in real-time is critical to ensure the integration of the digital design, design criteria, material properties and conditions particular to the construction method and the environment.

This new stage of robots in architecture allows architects to rethink construction processes, push robotic technologies and regain control over the fabrication process. Decisions regarding where in the process the humans and the robots are situated, how much intelligence is embedded in the robot and how much autonomy it has will have to be taken according to the materials, site, structural and shape constraints. It will result in new construction sites where new interactions between human, robot and material agencies are designed and negotiated based on the design objectives. By taking on this challenge and engaging in this process, architects have the opportunity to shape this environment according to their design intent.

5.2. Industrial "Cobots" and their potential in architecture

The urge to get the robots out of their cages has been noticed by the industry. As robots move away from their constrained, planned environments and move into our human, messy, unpredictable world to be our collaborators they need to become more elastic, flexible, gentle and aware of their environment [26]. 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 can be found in the robots developed by the Danish company "Universal Robots" and the recently introduced KUKA LWR lightweight robot.

▲ Figure 10. Left: Typical industrial robot. [5] Middle: KUKA LWR. [5] Right: Baxter. [44].

A different attitude to collaborative robotics is the one developed by 'Rethink Robotics' on 'Baxter', a robot with two industrial arms and a face, which allows the user to know what the robot is looking at. This robot presents exciting possibilities for the industry as it can truly work next to humans. Baxter gets taught by example with the human moving his arms to accomplish a defined task that he records and learns and that he then can repeat endlessly. While this approach works for repetitive tasks, robots in the context of architecture are mainly used for individualized production rather than repetitive processes. This kind of teaching will imply an enormous effort from the human programmer especially for non-regular geometries that are not easy to describe manually. In an architectural context, robotic production is concerned with unique parts that are usually designed and developed within CAD software and with more complexity that what can be manually taught to a robot [27]. Thus, a different way of engaging human–robot collaboration needs to be designed for architectural applications.

6. MATERIALS AND MATERIAL PROCESSES

In traditional architectural practice the information is derived from the design and imposed on a material. Materials are thought of afterwards and a complex negotiation happens to make them fit the design and vice versa. In this context it is important to search for new technologies and materials that might be better suited to the robotic era and that can evolve in parallel to it.

Digital 3D scanning and image capturing technologies such as Kinect, Skanect, 123Dcatch and others enable us to understand material behaviour, digitalize 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 through a feedback loop. This creates processes where the architect sets the various parameters based on fabrication techniques and material properties and adjusts them iteratively in the physical and digital models, until a balance between material properties, technical requirements and aesthetics is reached.

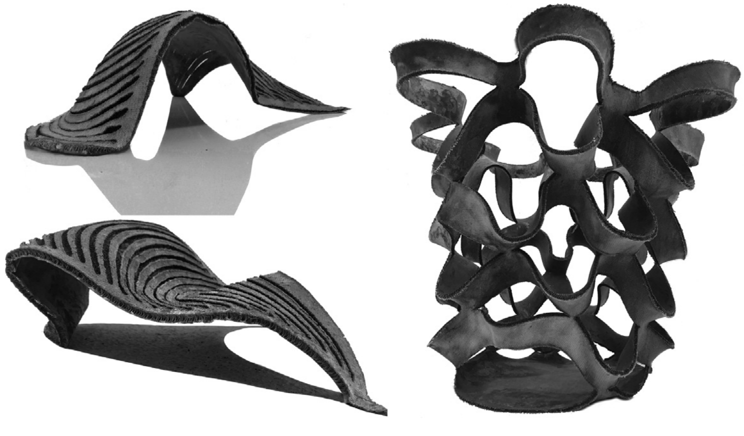
7. ROBOTS THAT FEEL, MATERIALS THAT FEEL

The presented analysis on the status of robotics, architecture and materials allow for speculation that we are at the start of an era of robotic collaboration in architecture where the robots form an integral part of the design process and, through the design of custom end effectors, can become an extension of the designer's hand. Similar to how sculptors and painters interact with their tools and artefacts, this process allows architects to set the parameters of the initial design and allow it to evolve through a collaborative process with the robot. The availability and lower price of sensors and 3D vision systems create a feedback loop between the material reactions, what the robot 'sees' and 'feels' and the human designer. They start to create a dialogue where the robot can ask questions and expect answers. Designing processes where humans and robots have agency and communicate with each other, will accelerate the deployment of robots on-site. The proposed digital fabrication process with the use of a new material technology allows the creation of an on-site production workflow that can feel and adapt in real time to the constraints and changes to the material, environment and structure. It increases the capabilities of robots to build novel and complex geometries and to explore new materials and techniques [28] through an iterative feedback loop with humans.

8. CASE STUDY

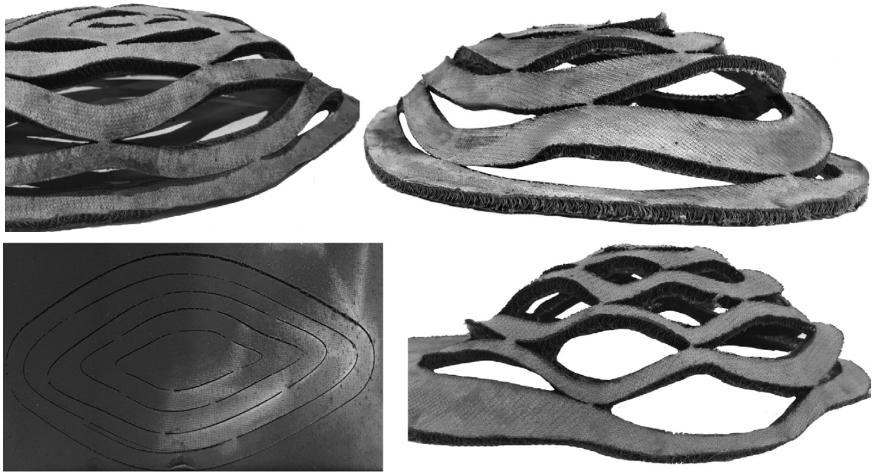
For this case study, flat packed, pop–up concrete structures were explored as a means to create a flexible and adaptable fabrication system for the creation of thin shell, complex concrete structures. A new material technology, Concrete Canvas, is explored in this process for its hybrid characteristics that blend fabric and thin-shell tectonics. Its potential integration to the robotic and architectural discourse is tested. Combined with a digitally controlled workflow of on-site cutting and inflation and an iterative material feedback loop, the process can serve as a radical alternative to current concrete fabrication techniques.

► Figure 11. Pop-up prototypes using Concrete Canvas.

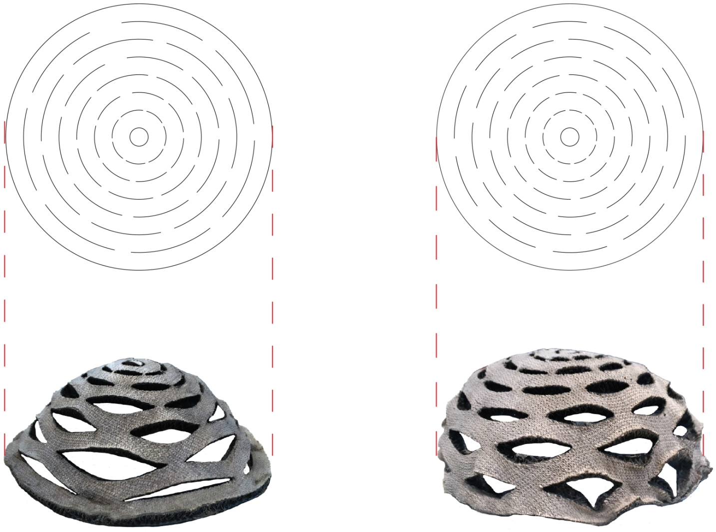


8.1. The setup

The concrete geometries rely on a parametric system of 2D cutting patterns performed in ‘concrete canvas’, that transform into a 3D shape by buckling under compression. This system set-up is done physically and digitally so that when the units pop-up they can keep continuously informing each other in an iterative feedback loop. The aim is to embed a pattern in the material that when it pops-up is capable of performing structurally while also achieving qualitative architectural effects. In this system, fabrication doesn’t come from transferring the form from the computer into the material but from embedding that transformative capacity within the material.



◀ Figure 12. Top: Different pop-up shells resulting from pattern variations. Bottom left: 2D pattern. Bottom right: Resultant 3D surface after pop-up.



◀ Figure 13. Changes to the cuts and joints 2D pattern have clear effects on the resultant popped-up geometry.

8.2. The material

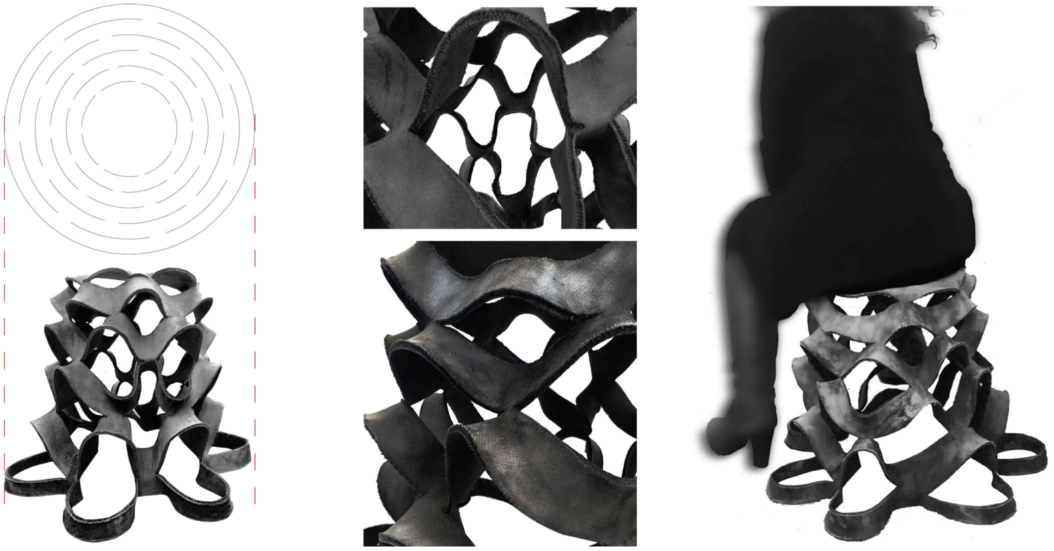
Concrete Canvas is a material that has the indeterminacy and free flow of fabric but when hydrated has the stable properties of concrete. Concrete canvas behaves similar to a very thick fabric formwork but it doesn't need formwork as the fabric, the cement and its reinforcement are sandwiched together. This condition allows for easy deployment and rapid construction of thin concrete shells. Given this duality, the material displays *probable* rather than *certain* behaviour. This characteristic allows us to assess the structural influence of the pattern of cuts and joints and the effects of its different variations during the pop-up process. The system uses inflation to pop-up into a surface. Through hydration, concrete canvas assumes its full shape, cures and becomes structurally rigid.

▼ Figure 14. Left: Concrete canvas section. Middle: Typical deployment sequence. Right: Traditional concrete shells made with concrete canvas [43].

8.3. Cutting and Popping

After conducting several tests we found that the best way to cut the concrete impregnated fabric and avoid any cement loss during the cutting process, is to hydrate it first. This means that the concrete has to be placed on-site before the cutting starts. Concrete Canvas has a timeframe of 5 hours after hydration where the concrete can still be manipulated before it starts to settle. A custom-made end effector was designed for the robotic arm that cuts the patterns on the concrete after hydration. Once the pattern is cut, the shape is secured and the inflation process can start. Future design and research will be done to build an end effector that is able to measure and control the inflation through the robot, so it can communicate this information back to the designer to make a decision at each step.

► Figure 15. Left: Setup and end effector for robotic cutting of concrete impregnated fabric. Right: 1.0x0.7x0.7 popped-up prototype.



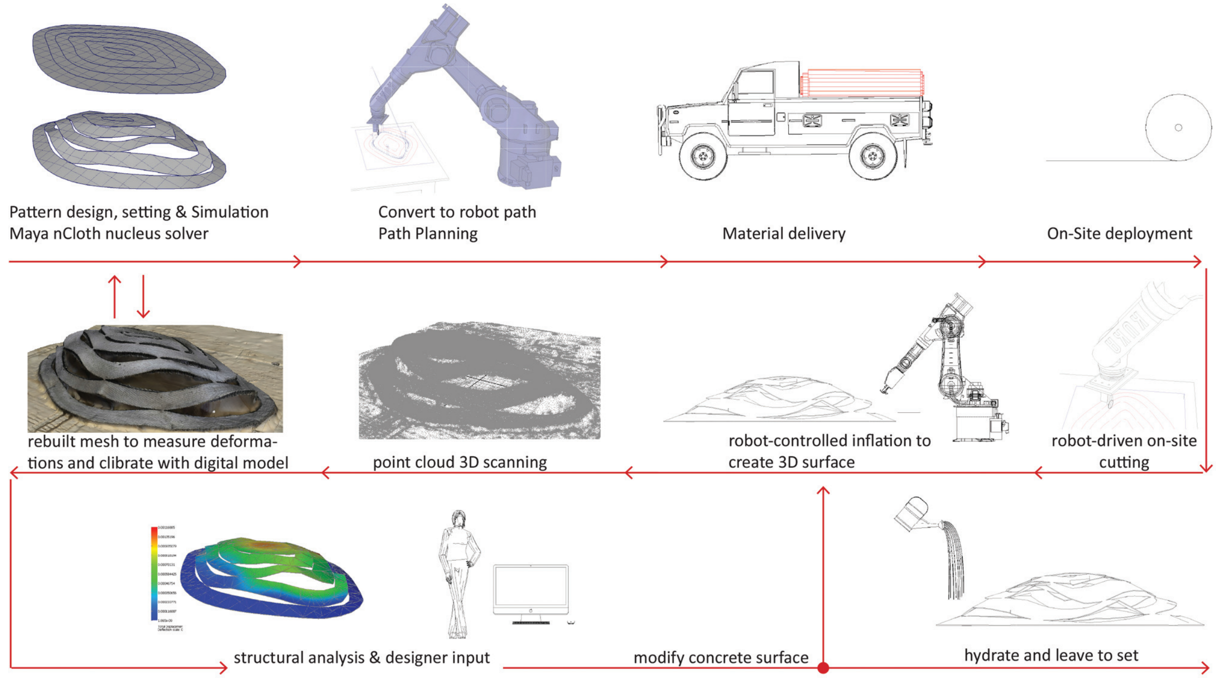
▲ Figure 16. Left: 2D pattern and resultant 3D geometry. Middle: Concrete details. Right: Live load testing of prototype.

8.4. The feedback loop

Taking advantage of new digitization technologies, the popped up shape is scanned and taken back to the computer for structural analysis, calibration with the digital simulation and design refinement. With this information the designer can continue modifying the inflation until equilibrium between material, structure and form is reached. Finally, the concrete is left to settle for 24 hours at which time the rigid concrete shell is ready to use. A feedback loop between the digital and the material is created and continuously updated during the form-finding / form-making process. With this system we aim to provide an option for the quick deployment of mass customized concrete shell structures. It aims for a production technique where modelling, analysis and fabrication are integrated; and where form emerges as a result of a negotiation amongst structural, material and design constraints. In this process the input parameters, transformations and resulting geometry are constantly adapted and relinked.

9. CONCLUSION & FUTURE RESEARCH

Traditionally, any change in the surface or shape of concrete structures is expensive, time consuming and labour intensive. By using this new material technology, the potential of digital design and fabrication processes in concrete was explored. The experiments presented in this paper searched for a connection between design and material where the form became a result of an iterative process of continuous evaluation between both. Pop-up structures were explored that create different 3D geometries out of 2D patterns that buckle under compression using a construction material like concrete.



▲ Figure 17. Path planning and feedback loop

3D pop-up geometries have an advantage over 3D printed ones as you can reach a space-enclosing surface faster. Further research will be conducted to understand how to design a 2D structure that pops-up into the desired 3D structure. A main challenge of this technique is that while the desired end 3D shape is known the pattern to produce it is not. This presents an inverse situation to that of traditional construction methods [29] and will require the creation of a taxonomy of pop-up structures. Pop-ups can be deployed on site, cut and inflated through a collaborative robot-human process and using feedback loops they can be analysed to understand their physical materiality. As a result, a new path is proposed towards the design of curved, thin, flexible structures in concrete without the need for a complicated formwork that would be otherwise required to achieve a similar form [30]. The next steps would be: First to set a robotic process for the inflation of the concrete canvas. Second, to make the feedback in real time from the physical models to the digital simulations throughout the robotic inflation process, for an iterative analysis where the designer can manipulate the shape before it sets by sending information back to the robot and modifying the surface in real time, until all the variables are satisfied and the concrete is left to cure.

Emerging technologies from robotics, cloud computing, sensors and synthetic biology are opening up new possibilities and processes in architecture. There is a need to define new design and construction processes that accommodate a new set of actors and our interactions with them. New developments, when integrated with digital practices, methods and techniques, can interlink geometric, structural and material performance [31]. The construction site of the future will be an ecosystem of different robots and humans working together and it is important to design the methods by which these processes will emerge and architectural designs will evolve in this new environment. The future of architectural practice will need to re-envisage human relationships to materials and technology and create more integrated and interactive design and construction workflows.

REFERENCES

1. Bechthold, M., "The Return of the Future: A Second Go at Robotic Construction," *Architectural Design*, pp. 116–121, 2010.
2. Bock, T. and Langenberg, S., "Changing building sites," Made by Robots?: challenging architecture at a larger scale, *Architectural Design*, vol. 84, no. 3, pp. 88–99, 2014.
3. Corke, P., "Introduction to Robotics, robot futures," https://moocs.qut.edu.au/courses/814/learn [25-05-2015].
4. Ewalt, D. M., "30 great moments in the history of robots," www.forbes.com, 2012 [15-02-2015]
5. Bonsignorio, F. , "The new AI and robotics: Lecture by Fabio Bonsignorio," (IJARS), *International Journal of Advanced Robotic Systems*, 2015. [Online]. Available: http://robohub.org/the-new-ai-and-robotics-lecture-by-fabio-bonsignorio/. [12-03-2015].
6. Windisch, K. G., *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, 2010.
7. Özel, G., "Case for an architectural singularity: Synchronization of robotically actuated motion, sense-based interaction and computational inference.," in *Proceedings of the 34rd Annual Conference of the Association for Computer Aided Design in Architecture,* ACADIA 2014, 2014, pp. 399–408.
8. Morel, P., "Computation of revolution," Made by Robots?: challenging architecture at a larger scale, *Architectural Design*, no. 229, pp. 76–87, 2014.
9. Gevarter, W. B., *Intelligent Machines: an introductory perspective of artificial intelligence and robotics.* Prentice Hall, 1985.
10. Daas, M., "Toward a taxonomy of architectural robotics," *Sociedad Iberoamericana Grafica Digital (SIGRADI) 2014 Conference*, vol. 14, pp. 623–626, 2014.
11. Braumann J. and Brell-Çokcan, S., "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, 2012.
12. Witt, A. J., "A Machine Epistemology in Architecture. Encapsulated Knowledge and the Instrumentation of Design," *Candide. Journal for architectural knowledge*, vol. 03, no. 03, pp. 37–88, 2010.
13. Feringa, J., "IaaC lecture series," https://www.youtube.com/watch?v=vSxjsdIbXp4 [10-03-2015].
14. Walz, A., Kilian, A. and Schindler, S., "Programming Knowledge," *Candide. Journal for architectural knowledge*, pp. 49–68, 2009.

15. Lavallee, J., Vroman, R. and Keshet, Y., "Automated Folding of Sheet Metal Components with a Six-axis Industrial Robot," *Proceedings of ACADIA 2011*, pp. 144–151, 2011.
16. Epps, G., "Robofold and Robots.IO," Made by Robots?: challenging architecture at a larger scale, *Architectural Design*, pp. 68–69, 2010.
17. Elashry K. and Glynn, R., "An approach to automated construction using adaptive programming," in: McGee, W. and Ponce de Leon, M., eds., *Robotic fabrication in Architecture, Art and design*, 2014, pp. 51–66.
18. Bonwetsch, T., Bartschi, R. and Helmreich, M., "BrickDesign," in: Braumann J. and Brell-Çokcan, S., eds., *Robotic fabrication in Architecture, Art and design*, 2012, pp. 102–109.
19. Keating, S. and Oxman, N., "Compound fabrication: A multi-functional robotic platform for digital design and fabrication," *Robotics and Computer-Integrated Manufacturing*, vol. 29, no. 6, pp. 439–448, 2013.
20. Blair, S. "IdeaHub, ABB launch new robotics accelerator programme," robohub.org, 2015. [02-03-2015]
21. Pfeifer, R. and Bongard, J., *How the body shapes the way we think*. Cambridge: MIT Press, A Bradford book, 2006.
22. Goldberg, K., "Let's Ditch the Singularity and Focus on Multiplicity," *World Economic Forum, Davos 2015*, 2015. [Online]. Available: http://robohub.org/forget-singularity-lets-talk-multiplicity-ken-goldberg-on-ai-at-the-wef/. [02-02-2015].
23. ElMaraghy, H. A., "Flexible and reconfigurable manufacturing systems paradigms," *International Journal of Flexible Manufacturing Systems*, no. 4, pp. 261–276, 2005.
24. Helm, V., "In- Situ fabrication: Mobile robotic units on construction sites," Made by Robots?: challenging architecture at a larger scale, *Architectural Design*, pp. 100–107, 2014.
25. Sakamoto, S. and Kumano, T., "Research and development of totally mechanized construction system for high-rise buildings," *International Association for Automation and Robotics in Construction*, pp. 197–206, 1991.
26. Nourbakhsh, I. R., *Robot Futures*. Cambridge, Massachusets: MIT Press, 2013.
27. Feringa, J., "Entrepeneurship in architectural robotics: The simultaneity of craft, economics and design," Made by Robots?: challenging architecture at a larger scale, *Architectural Design*, p. 63, 2014.
28. Gramazio, F., Kohler, M. and Jan Willmann, *The robotic touch: How robots change architecture*. Park Books, 2014.
29. Ye, B.C. and Tsukruk, V., "Designing two-dimensional materials that spring rapidly into three-dimensional shapes," *Science*, vol. 347, pp. 130–131, 2015.
30. Kotnik, T. and Weinstock, M. "Material, form and force," *Architectural Design*, vol. 82, no. 2, pp. 104–111, 2012.
31. Oxman, N. and Rosenberg, J. L., "Material-based Design Computation: An Inquiry into Digital Simulation of Physical Material Properties as Design Generators," *International Journal of Architectural Computing*, vol. 5, no. 1, pp. 26–44, 2009.
32. http://www.art-wallpaper.net/vintage-poster/Metropolis/index.htm [10-6-2015]
33. http://www.mindfully.org/Reform/RUR-Capek-1920.htm#2 [10-6-2015]
34. Publicity photo for the 1956 MGM motion picture Forbidden Planet http://www.messynessychic.com/2013/10/02/10-reasons-why-vintage-hollywood-sci-fi-is-still-so-good/ [10-6-2015]
35. https://mit.zenfs.com/1555/2013/05/Counterparts.jpg [05-03-2015]

36. http://skipsheffield.blogspot.co.uk/2012/08/a-robot-and-national-treasure.html [05-03-2015]
37. http://cyberneticzoo.com/teleoperators/1948-ge-master-slave-manipulator-john-payne-american/ [05-03-2015]
38. http://www.mediamatic.net/153767/en/vaucanson-s-digesting-duck-virtual-voices-1 [18-03-2015]
39. http://archive.computerhistory.org/resources/still-image/Chess_temporary/still-image/1-0.The_Turk.Granger_Collection_0059574_H.L02645400.jpg [10-06-2015]
40. http://brunelleschi.imss.fi.it/genscheda.asp?appl=LIR&xsl=paginamanoscritto&chiave=100548 [11-06-2015]
41. http://www.bustler.net/index.php/article/robofold_nominated_for_emerging_design_studio_at_the_icon_magazine_awards_2, 'Arum' sculpture by Zaha Hadid Architects. Image: Matthias Urschler [10-06-2015]
42. http://blog.metmuseum.org/alexandermcqueen/dress-no-13/ [11-06-2015]
43. http://robohub.org/architectural-robotics-shape-of-the-robots-that-will-shape-your-home-in-dom-reconfigurable-spaces/ [30-05-2015]
44. http://www.mantadesign.com/baxter-robot-designer.html [11-06-2015]
45. http://www.concretecanvas.com/ [08-02-2015]

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