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How Can Bio-Mapping the Foraging Excursions of Ants Translate Into a Prototype for Human Living on Mars?

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ABSTRACT
This research project converges myrmecology, computer vision and architecture together to bio-map the locomotion of ants in a spatial-temporal dynamic setup. What can we learn from the de-centralised, flexible and optimal way of living from ants? Despite no journey plan and no limit on the size of areas they explore, ants never find themselves in traffic jams [1]. A number of simple rules give rise to a much more complex system, allowing ants to overcome many environmental obstacles with minimum energy expenditure and assessed risk. Through a series of stigmergic experiments, whereby a Kinect V2 is used for tracking and recording movement, this study looks to translate a spatial template of algorithmic foraging excursions into a resource-poor prototype for human living in an Extra-Terrestrial (ET) environment.

1 INTRODUCTION
When I think about the many dystopian futures that paint negative visions of human society, a repetitive occurrence lies within them. They tend to draw on the selfish behaviour of humans. This is particularly evident in J.G. Ballard's 'High-Rise' fictional book. Set in a residential block that offers all services necessary for living, a lack of empathy and altruism reveals itself and the society sees a complete breakdown of social organisation. Chaos and anarchy ensue, transcending into barbarism and eventually death. How is it that the most intelligent species living on Earth should find themselves essentially killing off their own when faced with adversities of "fear, hunger and isolation" [2], instead of adapting and developing resilience? For way of comparison, we can look at the contradicting and holistically altruistic behaviour and socio-psychology of ants. How do they go about necessary life activities and hostilities, surviving and staying highly organised? What can we learn from them, and how can we use it to influence new environments that may then alter the way humans respond in them?

The queen in an ant colony has no power over others: instead they work together, with each individual knowing what to do for the colony to succeed. They are a "fundamentally democratic" [2] society, whereby career changes evolve from: nursing for young, to cleaners, to foraging (and defence). They are organised into working groups that segregate spatially – giving us reason to explore how we may promote optimal living for humans by optimising spatial arrangement. Whilst we are unlikely to copy an ant's lifestyle, we can look to them for inspiration. Combining this with the aforementioned theme of hostile factors, this project envisions sitting in an ET environment, such as Mars. How, in fact, would these foraging excursions over time be translated to reflect both the environmental setting, as well as shape human living, on Mars?

As Warren M. Brodey said, "evolution now must include evolving environments which evolve man, so that he in turn can evolve more propitious environments in an ever quickening cycle" [4]. This "evolutionary dialogue" [3] considers organism with its environment, understanding how they may influence one another. This project looks to perceive spatial configuration resulting from bio-mapping ants over time with a Kinect V2, building a computational translation of "the functional space of an organism" [4]. It starts with a qualitative study on how the world is perceived through an ant's sensory capabilities, then goes on to extract data from a series of experiments with ants. From this, a prototype for human living in ET/extreme environments will be realised. This project is broken down into three main tasks: capturing activity, data mapping their 2D/3D co-ordinates over time, and addressing the rationale and implications of this. For the purpose of this study, harvester ant species were used. The aim is to understand why certain behaviour/form is the outcome.

2 BACKGROUND
Humans have been living in complex societies for only several thousands of years, whereas ants have been doing so for over 100 million years [5]. Despite the same daily travel challenges as people, ants don't get stuck in traffic jams. Crowding, bottlenecks and slow movers are all things experienced by ants too in their foraging activities. When ants walk past one another, the ant carrying something heavy (food item) is given priority, and the other ant will move to its side [1].

Speaking with leading myrmecologist, Dr. Nigel Franks [6] from Bristol University, we discussed the interdisciplinary connection between architecture and biology. Quoting Winston Churchill, he said "we shape our buildings, and

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afterwards, our buildings shape us." Here, he refers to the effect that an ant's social nature of ants has on their environment and alterations of it [7]. They function collectively as though they are one entity. We can consider this on many levels from political to social, for example - through a person's desire to move to a city because of how they either feel there, or based on other's experience in such place [8].

It is interesting to note how both humans and social insects utilise space as a means of encoding social information; for instance, ants have separate areas for foraging, brooding, nest building, keeping debris and corpses aside [9], and humans too for private and public uses. This spatial organisation we see in these social insects is promoted by a "stigmergic nature" [10], whereby a trace left in the environment stimulates a feedback, or reaction, from another member. This concept will fuel the methodology in this study.

Basic needs for a human society to thrive include: constructing shelter, defence, gathering food and raising children. This requires some level of energy dissipation and organisation within a labour workforce. What if we then took away the centralised organisation and instead relied on a biological-based algorithm? [11] Harvester ants are chosen in this study because they are a species best known for their foraging capabilities, hunting predominantly for seeds, and occasionally being lured by honey/sugary sources [12]. We can build a perception of how a resource-poor living in an extreme environment (e.g. Mars) could work, both spatially and temporally.

3 RELATED WORKS

Bill Hillier, who wrote about strategies of effective design policies, explained that the mapping between "human behaviour and its spatial containment" [13] can be abstracted to "psycho-physiology and the environmental filter" [13]. From a practical point of view, mapping structures that communicate this relationship are used as "autonomic devices" to resolve challenges. From a research view though, the purpose of using a mapping device is to understand and improve them [13]. So in the same way, through plotting ant behaviour in a confined space, we create a mapping device that can be developed into an autonomic device, or prototype, that solves problems and optimises with time.

3.1 The Purpose Of Tracking

The mechanisms behind the biological algorithms present in the foraging excursions of harvester ants can solve real-world problems. These include: traffic organisation [14] (including the 'traveling salesman' dilemma [15]), economising energy, and minimising energy output for maximum food return – e.g. pheromones indicate the near-optimal path for ants to reach food.

Deborah Gordon, ecologist from Stanford University, has found that harvester ants, local to hot climates like deserts or Mediterranean countries, are biologically programmed to store food for several months and only hunt when it is worth the energy expenditure and loss of water. This is dependent on the rate of foragers returning to the nest in a very short amount of time [16]. Such a study serves the purpose of inspiring transport networks and managing traffic jams [17]; the use of sand and gel environments aims to shed light on this. Biologist Guy Theraulaz explained that "[ants] get together to form complex yet fully functional and reactive structures" [18], and this study hopes to apply this thinking to a prototype representative of simple rules leading to something more complex overall. Ecological success of ants lies in their ability to switch between one algorithm, or task/role, to another as needed. Moreover, they are able to find the near-optimal paths by following pheromones (static) as well as follow a backup plan in case of a glitch/break in trail in a dynamic environment [15]. This defines the flexibility and optimisation that such a system offers, both lucrative qualities for a prototype on Mars.

Inspired by Neri Oxman, whose research investigated biological behaviour stimulated by environmental factors, this study aims to address the gap of 3D tracking of insects. Oxman has used her bio-computational design research to synthesize between nature and man-made – this is a result of her investigation between an organism and its immediate surroundings. Neri and her team translated the "motion-capture data" [19] of silkworms with a 3D printer to create a 'Silk Pavillion' [20]. There are many ways to interpret the tracking of biological creatures, and feeding off this, my research looks to translate the tracking of ants to develop a spatial-temporal prototype for human living in ET/extreme climates, based on optimised paths depicted in an ant's biological algorithm.

The work of computational architect John Frazer examined forms and process that emerged from natural evolution. Common ground between this study and his reveals itself in the application of a biological system's optimisation capabilities. Frazer's work focuses on genetic algorithms (GA)/computational methods, whilst my research places more emphasis on social biological algorithms. Additionally, cybernetician Gordon Pask, highlights the relation between machine and organism and the conversation between them that starts to construct an intelligent environment [21]. This raises an interest in architecture adapting to positive feedback [22], much like the prototypes that arise later in this project do in accordance to ant trails.

3.2 Use of RFID Tags

Entomologists have used RFID tags to track animal behaviour: each individual member's change in position over time is captured. One key case study, based at the University of Lausanne in Switzerland [23] recorded each ant's position twice per second; this allowed them to recognise that ants make 'career moves' with time – progressing from nursing the larvae (nurses), to cleaning rubbish (cleaners), to foraging for the colony (hunters) [23].

Another study by Dr. Nigel Franks sees the use of RFID tags to "get each individual ant to identify itself" [24] and find out worker's tasks, methods of communication and decision-making for nest-finding. This led to the understanding of how tandem running displays a mentoring system amongst ants [25], similar to the release of pheromones when something good has been found [26]. Unfortunately I could not use this tracking system myself due to both access/financial cost of RFID tags and the difficulty in personally attaching a tag to each ant member, especially as an amateur ant keeper. Dr. Frank's studies did, however, raise the question about spacing of food. A scattered food situation would likely represent a scenario closer to that they would experience in nature, whereas a clustered one makes it easier for them: so how would the two scenarios affect their behaviour? Similarly, what effect would obstacles have on their journey/decision-making routes? These are much like the considerations regarding the use of complex transport systems in human societies to relocate goods where they are required [27].

3.3 Cameras and Sensors

3D ant tracking has also been achieved using an "image acquisition system" [28] that studies the moving kinematics of ants with 3D values. However, consisting of five very high definition cameras, also calibrated together with several infrared lights, it is also a very costly system. To adapt this to my project however, I could use optical cameras with either an IR sensor or Raspberry Pi, all calibrated and connected to one central system.

3.4 Kinect V2 vs. Wii Motion Plus

Both the Kinect and Wii devices utilise cameras and infra-red (IR) sensors, making them capable of tracking movement and objects. Whilst very comparable, the Kinect V2 has overall been reviewed a little higher, with its use even extending as far as to the military [29]. Moreover, there are more python image libraries and Java Processing libraries available for use with the Kinect, and generating point cloud data, making it a more suitable choice. Whilst there is a newer version of the Kinect boasting higher accuracy – the Microsoft Azure device – it is unfortunately out of reach with sales only in the US at the time being.

3.5 Video and Real-time Tracking

The video-tracking software named 'trackR' [30] went some way to inspiring the methodology used in this study; it performs multi-object tracking from videos while retaining individual tracker identities. To complement such methodology, mine will incorporate real-time tracking, which also allows for a 3D dimensional aspect. Biologist Simon Garnier, from Swarm Lab, has produced research with computational architect Dr. Tim Ireland on the passing of information through chemical cues between ants in a colony, and suggested that construction arises from the organisation of "individuals, their activities and their environment" [9]. This forms the basis upon which both the methodology will be built on, as well the analysis of the spatial templates that result.

4 METHODOLOGY

4.1 Part A: Animate Object Exploration in Spatial-temporal Dynamism

This section looks to explore the spatial-temporal dynamism of ants in their environment to develop a qualitative understanding of how ants distinguish their environment. This philosophical approach is inspired by Rosenbleuth, Weiner and Bigelow's cybernetics-rooted paper entitled "Behaviour, Purpose and Teleology", as well as Biologist Jakob von Uexküll's concept of 'umwelt'. The term is used to describe how organisms perceive the world using sensor (touch with antennae) and motor organs (smell and laying of pheromone trails), linking it to their subsequent behaviour [31]. The "intrinsically purposeful" performance of an organism is defined by a constant feedback loop. By mass communicating (quality and quantity) of food sources, ants work on a positive feedback loop [32] to produce a pheromone trail and recruit others in doing so [33]. This links to the aforementioned idea of 'stigmergy' and producing an 'active' region. Ants do not expand unnecessary energy [34]. Furthermore, pheromones not only indicate food sources, danger, and the queen nearing the end of her fertility, but also inform orientation. Their searching efficiency is maximised by these individual interactions. The mandible action from their jaws, defensive movement, and overall fluid movement come together to form a series of reactions to their environment. Ants perceive and navigate the world attaining towards a goal, where "survival and purpose intermingle" [35]. I imagine their world to appear like a monotone pixelated grid from their perspective, where each pixel is representative of a chemical cue or not, and then they make a binary decision (see Figure 1). This denotes how the 'social engineering' experiments are created for them.

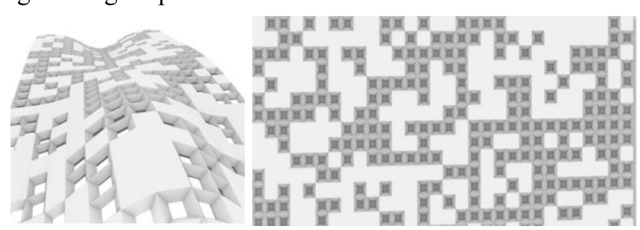


Figure 1. An ant's perception of the world.

An Organism's Perception and Response to Chemical Cues in the Environment

Organisms "detect and react" [36] to molecules in their surrounding environment, such as (hydrocarbon) pheromones, chemical cues warning of germs or predators, or pointing to food and shelter. Olfactory receptors allow ants to read the "biological barcodes" [36] which are the hydrocarbon molecules on the bodies of their nestmates. Therefore, this begs the question: how does an ant's ability to detect and discriminate between wanted (e.g. food) or unwanted (e.g. a repellent scent like cinnamon) generate different behaviour that can be tracked? More importantly too, could an architectural language be subsequently interpreted from this? This will be integrated into the methodology for the experiments in the next section.

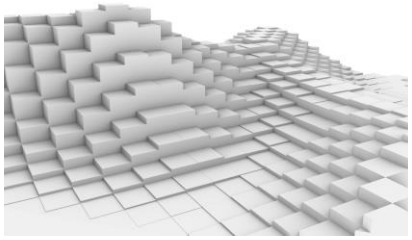


Figure 2. How individual decisions, based on chemical cues and interactions, add up to a fluid and collective movement.

4.2 Part B: Experimental Study

This part of the methodology looks to employ 11 harvester (Messor barbarous species) worker ants and a queen for the purpose of capturing their food foraging excursions with a Kinect V2, while influencing their paths (social engineering) over time. This is made up of the physical aspect of the organisms-in-environment, and the digital that allows them to be tracked and lead to a human prototype for living.

Computational Methodology steps:

1. Deep Learning: I used a single object image annotation tool (VoTT) to prepare/annotate 1000 images for ant detection and build in Yolo (darkflow) software (Real-Time Object detection) [37], using tiny-yolo weights.
2. Python with darkflow and Kinect V2: Now that the ants were recognisable by the system, the next step was to specifically track the movements of individual ants between frames/over time. Python libraries (openCV, darkflow, numpy and PyKinect2) were used to bring together the Yolo detection and the Kinect. This was done by getting the Kinect to return the depth information, then the centre of mass for all ants, and then the depth information for every ant. Finally, this data was recorded both in video format and as .csv format, storing each ant's ID and 3D co-ordinates over frames.
3. 3D prototype model: The final digital step sees the interpretation of the spatial-temporal ant trackings as prototypes for human living. This is done using the Wasp plugin for Grasshopper/Rhino, aggregating discrete modules that are essentially 3d modelled/printed along the ant traces.

Physical Methodology steps:

This part details the 'social engineering' that these experiments perform on the harvester ant colony. It is hoped that form and performance would be synthesized. The same ant colony is used per environmental setting.

Spacing of Food		Home (no. of nests)		Obstacle		Environment/setting		
Scattered (K1)	Clustered (K2)	1 (K0)	2 (K3)	Cinnamon (K4)	Perspex (K5)	Sand (K7)	Gel (K8)	Plain ant farm (K0, K1-5)

K6 represents the combinations from K2-5.

Table 1. Summary of experiments designed.

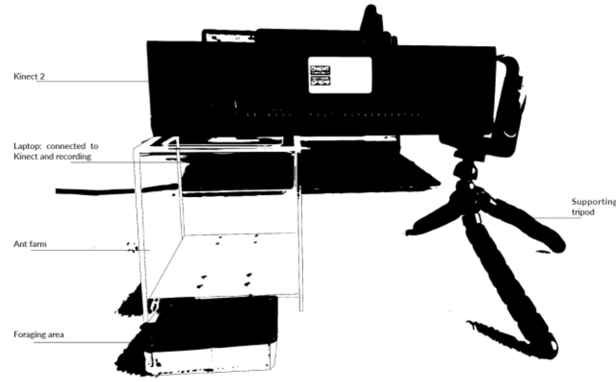


Figure 2. Setup using laptop, Kinect V2, and main ant farm. Experiments: Decision-making relating to foraging and nest-making/shelter, as effected bye environmental setting, obstacles and nest options.

Strategy

My interventions in their environment that aimed to encourage nest migration (for K3) included: tracing sugar trails towards the new nest, moving a couple of workers near the opening of the new nest, moving a couple of workers near the opening of the nest, adding food supplies and a red cover/lid to the new nest to immediately appear attractive.

1. Scattered: Food is spread around the main arena.
2. Clustered: Seeds are clumped up in two corners of the main arena.
3. Number of nests: This involves adding a connector that leads to a new nest. However this one is smaller than the first. Will they move, and if so how long will it take them to decide?
4. Environmental settings: Plain ant, sand or gel. White sand loam is used and it requires water to be mixed in until it visibly penetrates all the sand. Food is kept in the petri dish that is connected via tube. How does each affect behaviour or ease of tracking them?
5. Obstacles: One is a physical object – Perspex – cut out in such a way that it mimics ant journey paths and method of building, with traces of honey along it as a climbing lure. Cinnamon represents a chemical odour they find undesirable. This was placed along the entrance to the original nest, to see if it can deter/persuade them to relocate.

5 FINDINGS

Increasing complexity through experimental stages has given more opportunity to capture the transfer of information and resources by workers in their 'network analysis' [38].

Caring for the Ants

Initial difficulties found in caring appropriately for the ants include: the queen dying in the first colony (which shortened survival rate for the whole colony), a colony discretely escaping, and another colony not surviving in sand loam. This could be due to internal air temperature increasing beyond what it should have (due to strong sun and heat in the month of July), mould growth (toxic for a colony), and lack of sufficient moisture in their environment. To improve conditions, a humidity sponge was added for later colonies. The advantage of using gel is that it provides an environment where ants can both feed from and dig into, like they would earth, whilst revealing their 'underground' travels within the gel; this was the easiest to take care of. The ants would also pile up dead bodies and waste to the side – making cleaning easier.

Social Engineering on the Ants

I have been leaving hints or traces in the environment of the ants (stigmergy (Grassé 1995)), manipulating their opportunities and challenges [34]. Change of behaviour was recorded; at least one ant felt the need to explore the quality/quantity of a food source.

It was found that changing scenarios in the ant farm also led the ants themselves to change between clustered and scattered groups. It is evident that individuals stick to their role (foraging, defence, nest maintenance or brooding) unless temporarily recruited to fill other shortages [34]. Splitting up the colony temporarily in the sand environment, between the connected petri dish, saw the colony first appear lost but to self-organise within 12h. Most food was stored at the bottom of dug tunnels in the gel and sand loam.

Hardware

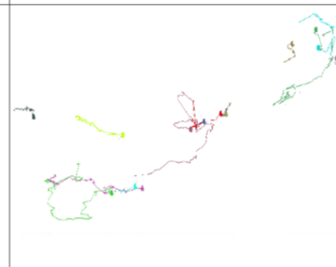
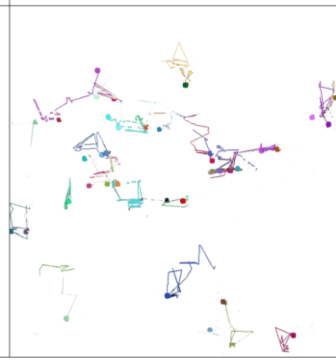
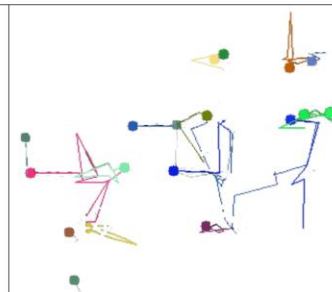
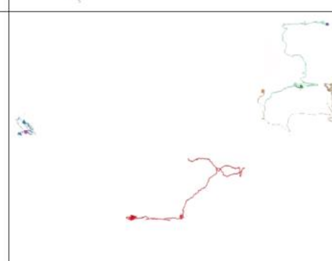
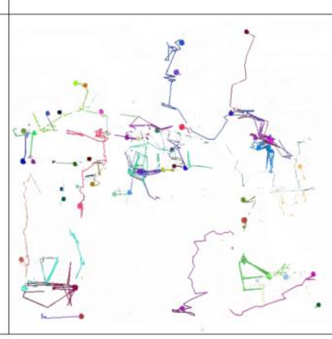
Limitations faced with the Kinect include camera quality, and size of pixel/object it can capture. Whilst this was partially overcome through YOLO/object detection, perhaps extended model training could have been put in place.

6 REFLECTION AND DISCUSSION

Increasing complexity through experimental stages has given more opportunity to capture the transfer of information and resources by workers in their 'network analysis' [38].

Due to the dispersion and vaporisation of pheromones, many of the results depict journey paths that "emerge, converge, fluctuate, and expire" [10] – which makes it hard to analyse the optimal route of an organism moving through a dynamic environment.

Aggregation Pheromones describes insects being attracted from a distance to cluster around a pheromone source. It is a natural evolutionary response to an organism's environment, as it may protect from desiccation and predators [32]. Just as their aggregation structure can be affected by environmental factors, so too can the architectural language and prototype that develops.

Exp	Spatial Template	Extractable Logic	Architectural Language
K0		Separation More individual work Prototype: describing arrival in a new environment	If we use the overall curve of the movement of the ants in this scenario as a boundary field, parts can follow and aggregate more heavily along the curve turns. This means more modules will cluster on those bends, as if to highlight their change in direction/decision.
K1		High interaction rate – lot of communication Geometric intersections Networking/ collective workings. Trying out lots of new routes until perhaps the decide on the most useful ones to take.	Just as the scattered food causes small cluster formations amongst the ant colony, here we see voxels aggregating along the field points driven by the ant networking trail. The prototype expresses the fluctuations in interactions over time too.
		Module: describing 'hot' foraging activity Repetitive modules: indicates this journey path works best for them	
K2		Individuals venturing to find best way (i.e. simplest) to food. Perhaps less successful than the other experiments, there is less of a specific language here.	This could be because it is likely their least challenging environment out of all the experiments: no over-excitement over many seeds everywhere, and no obstacles. Therefore no urgency to go out foraging perhaps. The overall movement can work as a field boundary line.
K3		Various tasks going on: foraging, nursing, storing food, cleaning. Upon feeling exposed, they might be communicating about the potential of finding another home, as there seems to be a lot of	Module extracted to express their repetitiveness and interaction:  In line with their need to be organised for their survival and make moves worth the energy expenditure, the prototype here

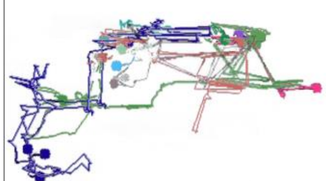
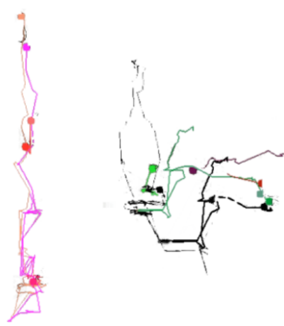
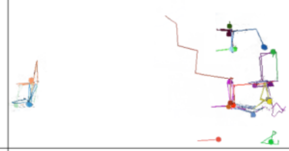
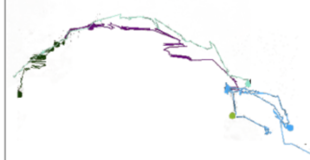
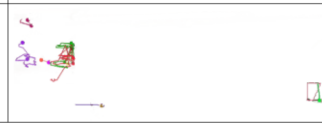
		interaction and movement. Short routes to find new food - stochastic behaviour.	expresses a more orderly aggregation.
K4		Tandem running likely to have taken place here – a type of mentoring system. Not all ants returned the same way that they went out, indicating that some optimised their paths with time.	There are two overlaying languages here: one is a more strict geometric/90 degree turns in this spatial template than some other ones, and the other follows slightly more erratic lines. Therefore, the two modules also have their own rules, or 'connection grammars'. These come together in one prototype through aggregating the ends, long sides, and short sides of one module to the other.
K5		Either avoid obstacles and create their own direct corridor, or work around them as closely knit as possible within, maintaining close proximity to fellow foragers Repetitive journey paths Disjointed	Modules derived from movement patterns (as a result of tracing over their most repeated geometric routes):  In line with their geometric pattern-making, we can translate their rules are directional, connecting the modules together through their centre. These parts can then be aggregated additively, joining together various faces of one module to another. Just like the ants navigate their environment, different chemical cues lead their decision making.
K6a (45)		Minimum energy expenditure – living as though resource-poor. Ideal for a living prototype in an ET/extreme climate.	-
K6b (234)		Optimised paths – short and near. Strong pheromones trails motivate the same journey paths.	-
K6c (245)		A kind of optimisation where one destination is more popular than another and so the route there is easier because there are chemical cues leading to it.	Finding the path of least resistance/difficulty towards a richer food source, can be expressed through a resembling sine wave field distribution, which is then modulated against the 3D co-ordinate points of their locomotion over time.
K7		Repetitive journey paths from many individuals – indicates strong pheromone routes and communicates colony's need to build. Most efficient way to dig through a solid ground to get there?	The ants building algorithm. The language described here expresses the consistent and continuous movement of aggregating one sand particle atop another – much in the same way, a simple module is aggregated atop the other along their movement lines. How we can create habitats that are dug into a solid environment, that are as efficient as possible, but create: e.g. an assembly hall, etc.
K8		-	-

Table 3. Detailed analysis and extractable architectural language from each experiment where possible. The different colours denote different ant identity.

Aggregation Pheromones

Just as ants use a combination of 'recruitment systems, with signals and pheromones from two potential glands [32], spatial templates like K1 use more than one type of module that aggregates in stochastic ways. Furthermore, ants also use 'tandem running' recruitment, where one ant is led to a "new nest of food source" by a "returning scout" – this seems likely for quite a few of the spatial templates, such as K2, K3 and K5, where we see either longer routes taken or an ant following a returning one. This can be recognised as field lines in some of the prototypes to follow. Foraging communication methods also allow for the colony to "retain a memory of previously rewarding locations" [32] and to be able to select between them. This would explain the findings in experiments like K6C, where I identified that there seemed to be a preferred food source, and also explicates how the ants knew to re-visit the one with a richer amount of seeds. Spatial templates, like K1 and K4 in particular, which show a lot of ants on the scene indicates a mixture of 'group recruitment' and mass communication took place – which entails recruiting a lot of their nestmates for foraging [32]. The journeys mapped are themselves a "communication network" [10] based on pheromone trails. It is also interesting to note that there is a lack of symmetry in all the spatial templates. This indicates a different route outbound than inbound over their foraging excursions.

In order to relocate, ants would need to see new benefits being offered, such as improved nesting. Whilst I did try to reduce attractiveness of their current home by removing the red lid (thus making them feel exposed) [24], moving away some of the food they had gathered and to stop adding as much moisture to their nest – the ants found it simpler to just re-gather food. They never moved and I realised this must be because relocation also has its costs: energy expenditure [39], potential loss of workers [40], reduced foraging time, and desiccation [41]. However, this is part of their biological efficiency and natural defence system.

Experiment Limitations

Some limitations were observed over the course of the study. Firstly, the ant farm setting is contained and so with limited travel distances, ants likely act in a different way than they would in nature. Environmental challenges such as finding a suitable nest site, establishing territories, defending against enemies, and traveling far to find food sources are all reduced [34]. Furthermore, temperature and humidity were not accurately monitored – this would greatly affect rate of evaporation of pheromones and in turn the way journeys are taken. This was not used as a variable though because it could kill the ants if not done with suitable sensitivity. Colony sizes used were relatively small (up to 11 workers) to ensure they could be tracked with ease, especially when near one another. Perhaps in the future, this could be expanded upon.

7 A PROTOTYPE FOR HUMAN LIVING

This section is a synthesis of the analysis so far and experimental results, where the ant paths are translated through fractalated voxels.

An Aggregation of Pixels

We know now that "ants don't waste their energy and share clustered resources" [42] - they only go out foraging as a result of positive interactions. Ants also know their limits and don't exhaust themselves. Imagine the system we could build for humans if we followed these simple rules. This chapter will therefore apply the outcomes of the experiments to a prototype for human living on Mars, an 'unreliable environment', where we assume life there would start out depending on resource-poor construction.

The models produced in this study are data-driven, fusing both theoretical/qualitative work as well as experimental. This will culminate in the translation of these "efficient collective decisions in unreliable environments" [43]. Ant behaviour is based on adaptability: according to the number of ants and changes in the environment, their architecture changes – much in the same way, a living building would need to alter according to environmental changes [18] and the symbiotic relationship between organism and environment.

Brodey described that "an aggregation of simple machines grows only into a complicate machine decomposable into simple elements" [3], much in the same way that ants follow simple rules to create a collectively more complex system [44]. The social algorithm of ants can be broken down into a series of binary decision points. At each decision point, an individual colony member either proceeds down one route or another until the next decision needs to be made, or the sequence ends. This is makes up the basis of their self-organised system. Thus, the aggregation of modules gives rise to a more complicated prototype. In the same way that some of the spatial templates display stochastic behaviour [32], the aggregation modules in these prototypes are too stochastically aggregated – i.e. different rules are applied in the additive process. Additionally, in the previous chapter we see the modules start revealing themselves in the spatial templates – what if these elements become fractalized modular pieces, aggregating together, translating each pixel of ant locomotion as a voxel? We can now consider how discrete modules could be used to realise this into a prototype that is customised to evolve space for specific needs.

Discrete Architecture

A computational design theory that approaches abstraction in architecture, known as 'Discrete' or as 'computational mereology' [45], loses focus on the holistic and instead prioritises its parts. Similar to the brushstrokes in Rothko's abstract art that are concerned with organisation through parts, architects of this movement concern themselves with "organisation of material parts or particles" [46]. Mario Carpo, architectural historian, has also described computation as an abstract and discrete process [47]. Also of interest, is that the post-capitalist technology employed works to "democratise and decentralise production" [48] with its automation, which in itself is also reminiscent of the democratic and decentralised organisation of the ant society. With this in mind, the architectural prototype that emerges from abstract parts can even be configured from "extreme discretisation of statistical pixel values" [45]. This is similar to how ants perceive the world in bits/parts, how they make their binary decisions, and how their trails are made up of each pixel/ant over space and time. This method of aggregational architecture is also fully reflective of both the process and findings produced in this study – the spatial templates are in themselves pixels of "coarse discreteness" [49].

Furthermore, in our consideration of material organisation that is indicative of big data organisation, we also lean towards a type of discrete assemblage and fabrication. This allows parts to be disassembled, and then aggregated with differentiation [50]. Much like how the ants avoid entropy through ascending adversities over time, this kind of fabrication too holds "low-entropy heterogeneity" by being feasible and cheap due to 'serial repetition' [51]. This makes it especially suitable for a hostile environment like Mars.

As such, the data collected from the experiments has been input to a multi-object behaviour library, effectively creating scenarios for human living in an ET setting. Some of the outcomes can be seen below.

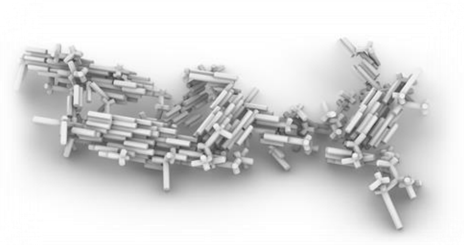


Figure 4. K4 3D prototype made up aggregated parts representing ants following chemical cues in their environment in a spatial-temporal sense.

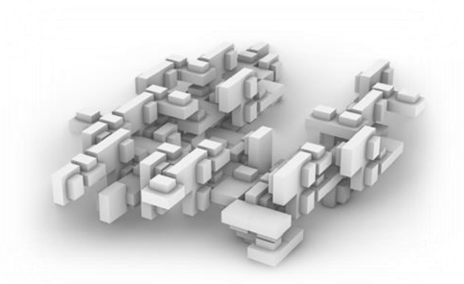


Figure 5. K5 3D prototype.

8 CONCLUSION

This interdisciplinary project has undertaken experimental research in the social organisation of ants, showcased through observation, bio-mapping their locomotion as affected by their decision-making in varying situations with increasing complexities over time. This study has extracted their biological behaviour to apply to spatial organisation in architecture, expressing their activities as a "dialogue between the subject and its environment" [10]. Every trail has a purpose and intent, which defines organisation, and results in a "spatial intelligence" that articulates the actions of these algorithm-guided individuals as a pattern [52]. These spatial templates are in themselves a "social product" that has unfolded as a result of interaction [53]. However, just as ants run on algorithms and know what to do, an intelligent architectural environment for humans wouldn't think like us. Rather, it would be capable of "rational autonomous action" that optimises the surrounding functions [21].

In this concluding chapter, I come back to the fictional story of 'High-Rise' to finish the comparison between man and ant, with themes revolving around resilience and optimisation. In the face of growing adversity over time in a fixed environment, the ants behaved in the polar opposite way to people. Much like how entropy deduces that chaos increases with time, as was the case in J.G. Ballard's story, the ants actually became more organised and worked better together. They were more wary of energy expenditure, organisation, colony survival, and teamwork (which comes in the form of group recruitment, mass communication, and tandem running). By following algorithms, worker ants avoid chaos, while still acting in a timely fashion [34]. Moreover, if an animate object and machine could self-regulate, then the chance of entropy are reduced through information return [21], as it adds control to the situation.

Ultimately, the concluding prototypes are a type of nest morphology: it shows how an organism has reacted to its environment, and the communication that has occurred between workers. The voxelated formations can be considered as frozen moments in time as the ants trace through their environment. Basing this process on a set of general rules that extracted from their biological algorithm acknowledges the balance of objectives against efficiency. The implications of this is the concept of an intelligent environment [3] – entailing "complexity, self-organisation… [and] responsive" as it perceives and reacts to surrounding stimuli [21]. The evolution in ants has also taught them to avoid disease and produce high productivity workers [54] – which hints ability to help even in medical fields.

Social engineering on the ants allows us to gain an understanding of how ants problem-solve. This is a key aspect of space syntax. Each pixel of ant movement over time in space is interpreted as a part, where they aggregate as a result of stochastic patterns, boundary field lines, and rule grammars regarding connecting faces and edges. Indeed, the olfaction of ants has created a new (3D) architectural language for responding to the environment. As we see from the prototypes, there are a lot of combinatorial possibilities and no finite answer. This, along with their possibilities of being easily disassembled, offers greater flexibility in construction and spatial arrangement – making it especially adaptable. For an environment like Mars, resilience would be another key factor. With its difficult atmospheric conditions, the situation lends itself to the creation of habitats that are dug into a solid environment as efficiently as possible; these studies have revealed some economical possibilities of digging through. This in itself starts to answer how the setting of Mars would alter human behaviour and living. Just as our buying and selling habits set market prices, and frequently visited websites contribute high rankings on Google searches [7], we can understand how we shape something bigger and more complex than our individual self.

The proposed prototypes are an offspring from the new knowledge gained about ant's behavioural relevance to architecture processes and products in creating a resource-poor living that would be feasible in an ET setting. A step further would be for the system to self-repair materially too, and to consider a more compact living arrangement for thermal and economic efficiency in an extreme environment. Therefore, further research could see these architectural aggregations optimized for extreme thermal environments.

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