RAF | A framework for symbiotic agencies in robotic – aided fabrication

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ABSTRACT

The research presented in this paper utilizes industrial robotic arms and new material technologies to model and explore a different conceptual framework for 'robotic-aided fabrication' based on material formation processes, collaboration, and feedback loops. Robotic-aided fabrication as a performative design process needs to develop and demonstrate itself through projects that operate at a discrete level, emphasizing the role of the different agents and prioritizing their relationships over their autonomy. It encourages a process where the robot, human and material are not simply operational entities but a related whole. In the pre-actual state of this agenda, the definition and understanding of agencies and the inventory of their relations is more relevant than their implementation. Three test scenarios are described using human designers, phase-changing materials, and a six-axis industrial robotic arm with an external sensor. The common thread running through the three scenarios is the facilitation of interaction within a digital fabrication process. The process starts with a description of the different agencies and their potentiality before any relation is formed. Once the contributions of each agent are understood they start to form relations with different degrees of autonomy. A feedback loop is introduced to create negotiation opportunities that can result in a rich and complex design process. The paper concludes with speculation on the advantages and possible limitations of semi-organic design methods through the emergence of patterns of interaction between the material, machine and designer resulting in new vistas towards how design is conceived, developed, and realised.

1. BACKGROUND

In this pivotal time when much rewriting of contemporary history is happening regarding how architecture is conceived and how it is produced (Speaks 2011),

This paper focuses on developing a framework for symbiotic agencies in robotic-aided fabrication through an analysis of the different agencies, their influence on the design process and the examination of several case studies. New digital tools, and more specifically robots, are often thought of as an extension of the designer's hand. Through iterative feedback mechanisms and observation of the relations created between the designer and the robot, this paper 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 and fabrication.

Although industrial robotic arms have existed since at least the mid-1960s within specialist environments, it is only in the last two decades that they have started to colonise other locations. Robots and, more specifically, robotic arms, are not a black box that will change construction in the future. From the moment Gramazio and Kohler started their laboratory at the ETH in Zurich in 1995, robots in architecture have been concrete things with character, limits, and influences. If architects are going to work with robots, it is important to define the means and frameworks for collaboration, to design potential interactions and choreographies with them. Robots invite us to rethink the traditional unidirectional workflow from 'digital design' to 'physical production' that currently exists in construction and digital fabrication processes, to use them as more than just another fabrication tool.

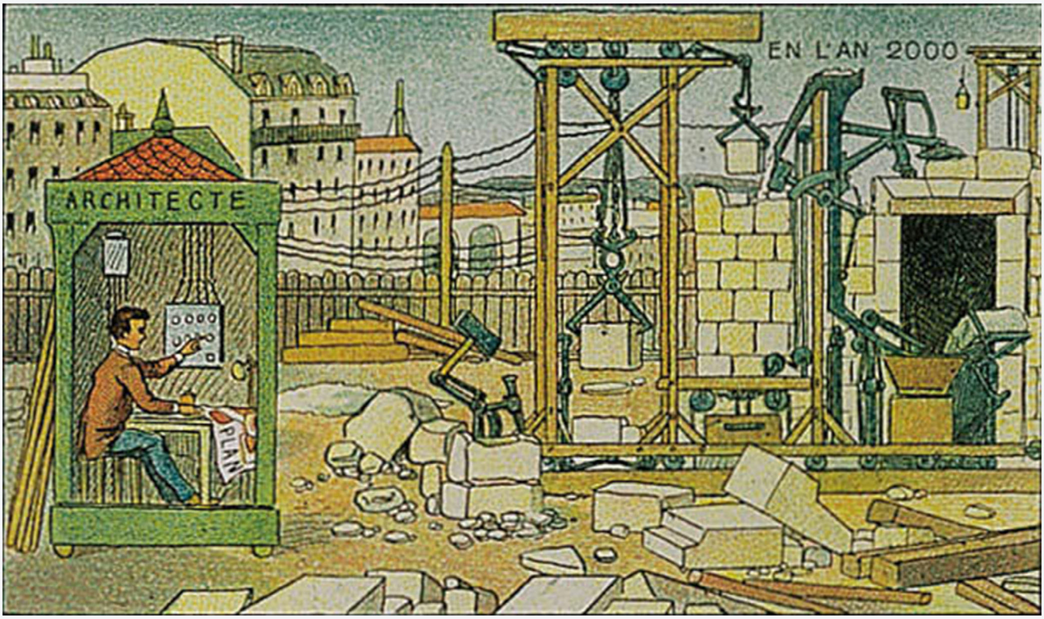
The cultural impact of techniques is undeniable. Lewis Mumford, in his book *Techniques and Civilisation*, clearly correlates the changes in the physical environment at the beginning of the 20th century, after the Industrial Revolution, with the changes in the mind. He rejects the idea that techniques can develop in isolation, uninfluenced by any other human desires than those from the people directly connected with their invention (Mumford 1959). 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), as robots become more ubiquitous in architecture this scenario is likely to change. A future is foreseen where multiple agencies from human and non-human origin interact collaboratively to create better designs.

This paper starts by describing each of the agencies: robot, human, material, and their importance in the architectural process. Then it proceeds to analyse, through case studies, different interactions with varying degrees of participation from the different agents during the design and fabrication process. The exploration through the case studies is centred around the creation of physical objects inspired by an iterative feedback loop between the material, designer and a six-axis industrial robot. The pedagogical approach includes an emphasis on learning-by-design for various computing tools, and their interaction and feedback with the 6-axis industrial robot with a focus on the connections between design intent, computational logic, and physical realisation.

2. ARCHITECTURE HISTORIC DIVISION

Since the Renaissance - some consider it to have happened during the 12th Century (Lloyd Wright 1901) - architecture has seen a division between intellectual work and manual production. Leon Battista Alberti's description of the architect in his influential treatise *De Edificatoria* makes a very 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). For the last 500 years this method of designing and building remained unchanged (Sheil 2010). Architects designed and prepared drawings, which evolved through the engineers and other specialist analysis to end up fully detailed and costed. Buildings were built, forcing materials into form, corresponding as closely as possible to the original drawings. There were architects who disrupted this relationship, such as Jean Prouvé, Charles and Ray Eames, and designers at the Bauhaus, who 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 and making in architecture.

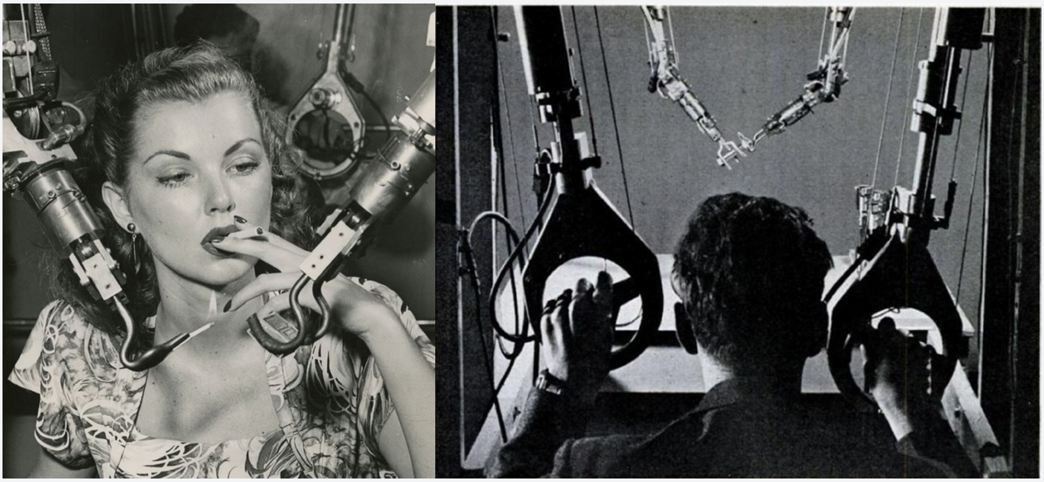
Computers gave architects a new tool for the study and creation of form. They introduced the ability to create and manage greater complexity than that which could be managed



▲ **Figure 1** Building Site of the future (2000) as envisioned by Villemard in 1901. Source: www.paleofuture.com

manually (Lynn 2008). Virtual models allowed new freedoms, but some of these forms could only be pursued at great expense. 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 more importantly about changing the relationship between thinking and doing (Speaks 2011). It shifts the production conditions towards making manufacturing a continuation of the design process.

Jean Baudrillard asked: *"How can automation be smart if it makes us simple spectators?"* (Baudrillard 2005). 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 building a brick wall (figure 1). Research and experimentation in digital fabrication seems to be approaching that scenario, moving the architect into the role of a mere spectator, an outsider button-presser. Hence, there is a need to develop a framework for robotic-aided fabrication that allows us to redefine 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 we need a framework that allows the robot, in collaboration with the designer and the material, to create a difference that is meaningful. The proposed framework for robotic-aided fabrication includes various steps: the architect 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, informing each other through an interactive human-robot symbiotic process that brings design and making closer, thus rendering this division obsolete.



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

3. SYMBIOTIC PARTNERSHIP

A human-robot symbiosis is different from the human-robot systems currently permeating architecture research laboratories and schools (Gramazio et al. 2014; Picon 2004; Gramazio & Kohler 2008). Creating this kind of interaction requires a creative design approach that takes into account the designer's needs, material criteria, and machine possibilities, especially as it involves appropriating a machine that has neither been developed nor optimised for use in architectural tasks.

Traditional symbiotic partnerships between human and machine, as laid out by J.C.R. Licklidier in 1960, 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). He already anticipated that through these symbiotic partnerships man would be able to perform intellectual operations more efficiently than alone.

During the 1960s with the advent of computational systems, ideas emerged in architecture regarding how these new methods could allow architects to give some control over the design to the end-users, allowing them to shape their living environments (Vardouli 2013). These ideas were reflected especially in the works of French architect Yona Friedman and the Architecture Machine Group at the MIT. They raised questions about authorship and performance: who performs the design? 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 model can be asked. In this case, it is not for a non-expert-centred model, as in the 1960s, but for one that redefines the roles and skills of experts in a design process wherein robots can overcome being used only as new building machines and become agents in a participatory fabrication process.

4. DEFINING THE ROBOT

There are many kinds of robots with great potential uses in architecture. For the context of this paper, "robot" refers to a six-axis industrial robotic arm. Industrial robotic arms have been in use in the industry since the 1960s. They are a proven, robust, off-the shelf platform that is flexible enough to accommodate the needs of the designer (Braumann & Brell-Çokcan 2012). 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 & Beesley 2014) and only become specific through custom-designed and built end-effectors. In this scenario, the designer does not need to concentrate on the design of the robot but on the design of the end-effector or tool that the robot will use and, more importantly, can focus on the design of the process.

The main human-machine interface for robotic arms is the teach pendant. 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 & Lin 2014). Technological developments have allowed for sensors to be implemented as an alternative method to control the robotic arm through body movements. Although this allows for more intuitive forms of control, it can only be used for simple movements. Robots are not smart tools; they rely on offline programming sequences and will only do whatever they are programmed to do. Through the addition of sensors, 3D scanning technology and cameras we can equip them to become aware of their surroundings and react to certain conditions. These technologies can enhance the link between the digital data, the designer's intentions, and the material behaviour. At this stage, robots are not able to make decisions by themselves in settings like construction sites or in the design process. The development of a real human-robot partnership becomes crucial, as humans are better equipped to make judgement calls while robots can consider the whole picture and carry out analysis.

5. AGENTS

There are various definitions of agency and what an agent is. However, the preferred definition for this paper is that from Michael Callon and Bruno Latour who define an agent as "*any element which bends space around itself, makes other elements dependent upon itself and translates their will into a language of its own*" (Callon & Latour 1981). A description of the different agencies and their potentiality is presented before any relationship is formed.

5.1 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 processes is still ambiguous. Four scenarios are envisaged that allow for 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: 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 human-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;
- As a coordinator or regulator where robots make alternative decisions in human situations, as they can have a more comprehensive perspective, using their computing ability to process large amounts of information (Lem 2014); the robots only provide advice and it is the humans who make final judgement calls: this perspective merges the computing strength of the robot and the perceptive strengths of the human;
- As a consultant, who is called upon to help even if it does not agree with the personal premise of the designer (Friedman 1980).

Robotic-aided fabrication aims for a scenario in which robots enhance human creativity by giving designers an insight into their own creation and materialisation process. The degree of agency they have in the process will be defined at the point where architecture absorbs this new connection between computational logic and material realisation.

5.2 Human Agency: The Role of the Architect

Humans are constantly immersed in a physical world. Human agency is then regarded as a subjective first-person perspective on one's way of reacting to and acting within the world (Malafouris 2008). Professional identities in architecture are diverse and dynamic. The role of the architect has varied throughout history- from the poet master-builder that frames all other arts inside his edifice (Lloyd Wright 1901) to 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 enough understanding to allow the execution of a design vision. The ubiquity of computers, simulation, representational and generative software and their increased use in architectural practice has convinced an increasing number of architects to give up their position as generalists in favour of establishing islands of expertise (Schon 1984) that span the areas of coding, geometry specialists, CAD managers and BIM consultants.

Computers have become central to the architectural workflow, increasing connectivity and enabling collaborative modes of practice between architects, engineers, and specialists. Additionally, they have blurred further the already ambiguous boundaries that separate architects from engineers (Loukissas 2012), since 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) –a situation that is still polemical and even conflictive for some architects, who feel that seeing the computer as an intelligent tool diminishes their knowledge.

5.3 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). 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, as can commonly be seen in craft processes, and one that is characterised by continuous dances of agency, resulting from the coupling of mind and matter.

The concept of material agency has recently entered the architectural discourse(Picon 2004; Gramazio & Kohler 2008). Alberti once said, *"It is quite possible to project whole forms in the mind without recourse to the material"*(Alberti 1988). In architectural practice, materials have traditionally been used to construct a built version of an idea that was determined in advance. Designs after conception are subjected to complex processes of rationalisation where tension occurs between the material and the form due to the initial disassociation between them. 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 design model to code to robot. (Bechthold 2010)

New developments in 3D scanning technology such as Kinect and cloud scanning applications (e.g., Autodesk 123D Catch) have made movement between the digital and the physical easier. These applications allow the analysis and simulation, and experimentation with material properties, and of new material configurations to be better and faster than ever before. By giving us a deeper understanding of material behaviour, they allow craft as an approach to making rather than as a specific way of making (Sennet 2009) to become an active agent during the design and materialisation process. In this context, craft and material agency refers to form being developed following the potentials of the material rather than it being conceived by the architect and then imposed on passive matter (Protevi 2005).

6. 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 with 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 the 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).

Understanding the implications of robotics in architecture requires a broad view of how they affect the system and its relationships. It requires integrating the parameters and principles of the robot with the material intelligence and human agency on site. Robotic fabrication allows the designer to get "*closer to the analogue and material world by mastery of the digital world*" (Sheil 2012) 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 constraints for their interactions. The robot becomes the coordinator that can oversee the whole project, guiding the process of formation, in which the architect makes the final judgement calls.

Matter and material behaviour are implicated in the geometry itself (Reiser 2006). 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. 3D-scanning technologies and robotic vision then capture the complexity of these phenomena and present them to the architect and the computer to analyse before the next move. This process differs from cybernetic attempts in the early 1960s that were very open-ended towards the user input. Here the machine has a defined human goal that it is trying to achieve.

As the new architectural process finds its place, the other agencies involved in the 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 robotic-aided fabrication, architects are conducting material research, robotic research, geometric design, and are also designing their interactions. This situation will not continue indefinitely. Engineers, contractors, regulators, builders, and consultants will also have to find their roles and the robotic process will need new expert roles to be created. Architects will need to reframe their work and skills around these new agencies and negotiate this 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). Robots are changing the discipline, redefining its relationships and boundaries, similar to other disciplines like physics; the first experimenters struggle to position themselves within the established categories until eventually altering them (Galison 1997).

"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, 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 unidirectional control, and 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, in which the architect becomes and active agent through the materialisation process and diverse agents have equal influence on the final design will be required (Carpo 2011).

7. CASE STUDIES

The following three case studies have been selected to illustrate a range of design interactions that the authors organized and investigated between human and industrial robots during the design process. The interaction in each case is positioned on different parts along the design-fabrication continuum, offering an opportunity to study and speculate on different approaches to human-robot symbiosis in architectural practice. The case studies were setup in a way that allows for identifying the potential productive connections between materials, machines, code, and humans. 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. As an active designer, he brackets the possibilities of the system through the different stages based on an analysis of the behaviours of the other agencies. The last two case studies address material variation as a creative force (DeLanda 2004) that allows us to incorporate difference and feedback during the fabrication stage. By studying them, we can identify the skills and toolboxes that define the new role of the architect as an active agent during the design and fabrication stages.

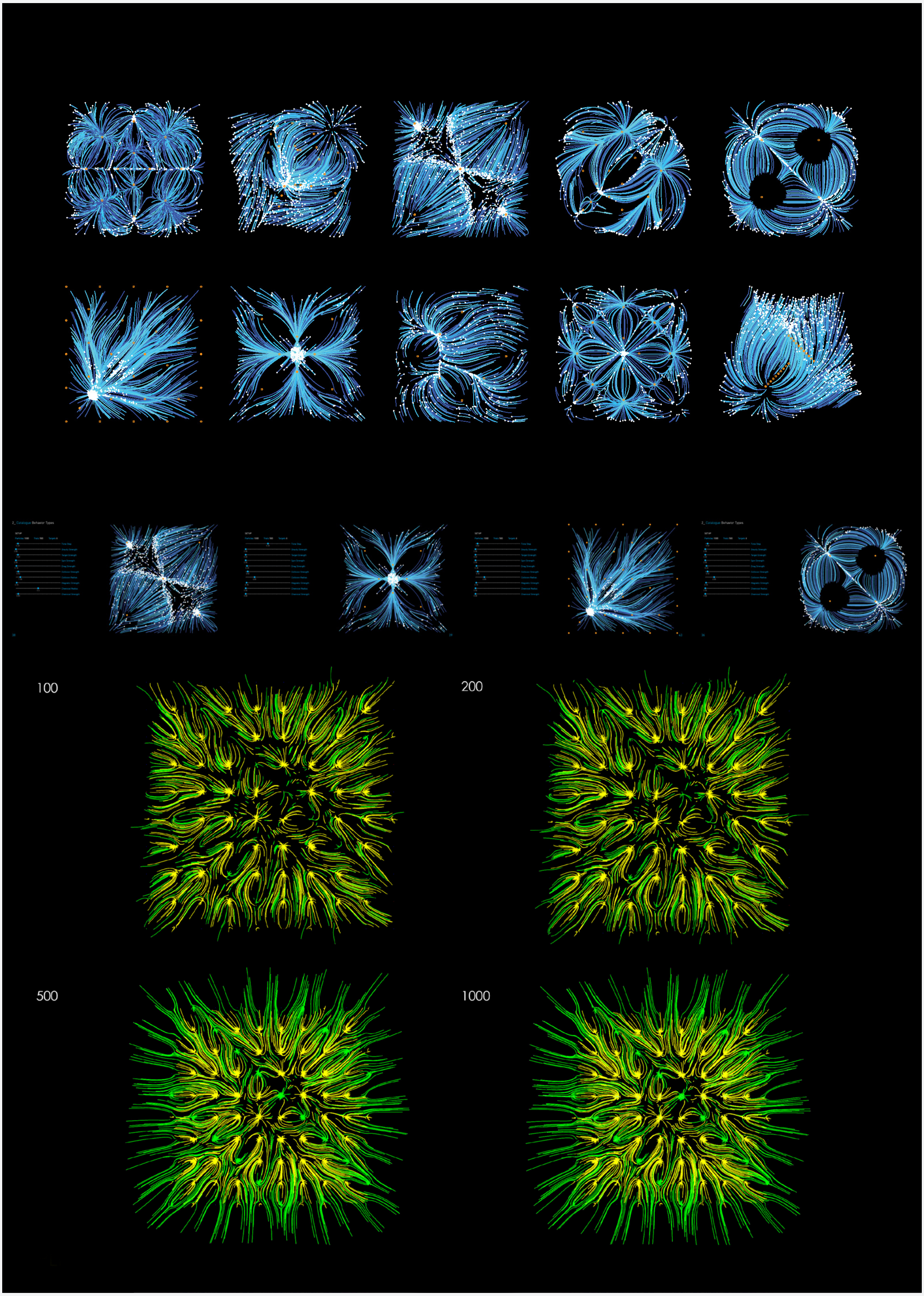
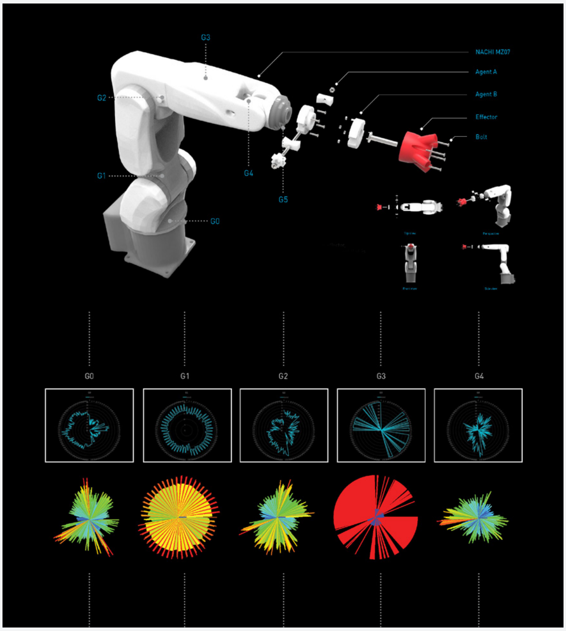


Figure 3 Catalogues of generative design patterns from particle system behaviours and their parameters



▲ **Figure 4** Top: Design of end effector. Bottom: Analysis of movement of each robot axis for optimisation.

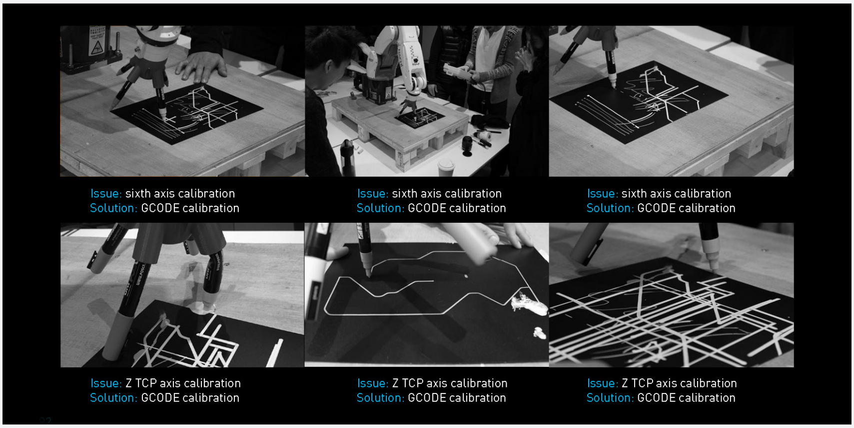
▲ **Figure 5** Physical robot setup. Team 1

7.1 Instructing Machines

A three-week workshop was taught in collaboration with Shajay Bhooshan, Vishu Bhooshan and David Reeves at the Architectural Association Design Research Laboratory M.Arch (AADRL), London, UK.

The case study "*Instructing Machines*" was run in November 2015 with AADRL graduate students. The focus of the workshop was to introduce code as a generative tool to instruct machines such as the computer and the robot and to analyse their output. It started with an introduction to the C++ language as a generative tool for designing patterns based on attraction-repulsion particle behaviours. After experimenting with this, the next step was choreographing the robot behaviour with the geometric moves by generating the G-Code from this same platform. Students worked in teams and the workflow included: generating the particle system, understanding the parameters and behaviours of particle forces, learning the constraints of the robot, incorporating them into the generative code, and finally converting the result into a set of points which could be followed in the physical world by an industrial robot. Students had the option of using the robot for either drawing or stippling their set of points onto paper. A Nachi MZ-07 6-axis industrial robot with a 7kg payload was used.

One of the initial facts that became evident when students were introduced to a robot arm for the first time was that, contrary to other machines that have a defined use, a robot arm cannot do anything without designing its tool or end effector. Students had been told to use it for drawing or stippling, so the first task was to design a tool that could handle a marker or a needle. Secondly, given the number of tasks that a robot arm can perform, its movements can be optimised in multiple ways. Its inverse-kinematic system can reach the same point in many possible configurations; some of them can be better for speed, for load, for torque, etc. For some points there can be multiple, nearly infinite, numbers of

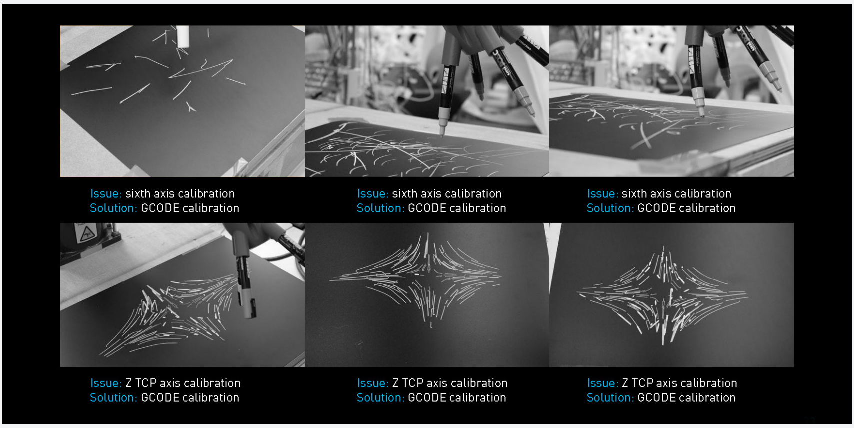


▲ **Figure 6** Robot instruction, analysis and calibration

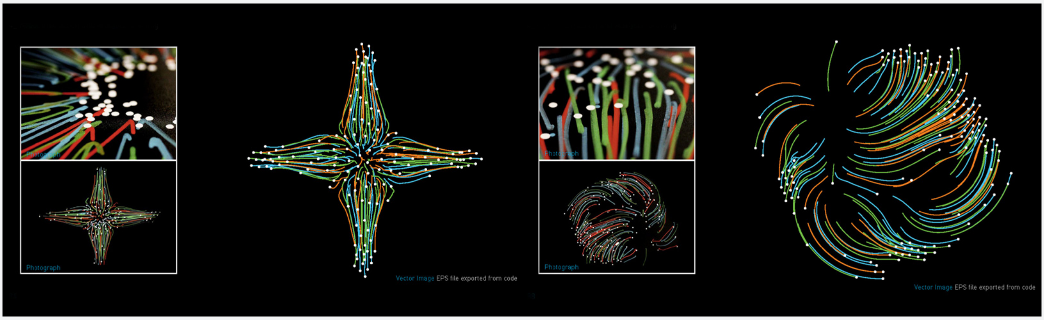
solutions. There is also the possibility of zero solutions if the point is out of the workspace or at an impossible angle for the end effector. Without a defined tool, a single optimisation procedure and the possibility of multiple solutions for the same task, the designer is forced to think about the steps and the final result that he wants to accomplish in order to decide how to plan its motion, generate the code, and optimise its output.

The Nachi robotic arm, unlike other robot brands, compiles its code directly in the software and not in the controller so a live link can be established. This means that changes to the robotic path can be made directly from the computer. The pre-developed design program that the students were using combined the generation of the particle simulations and the generation of the G-Code for the robot inside the same software platform. This meant that changes to the attraction and repulsion forces of the particle system, and hence to the drawing pattern became immediately apparent as changes to the robot movement trajectories. This direct relationship between pattern generation and the robot's movement meant that the design and its physical representation were directly connected. The designer becomes an editor of the generative parameters of the system, as set out at the beginning, and hence of the output, without directly designing the final product, but by controlling the digital and physical parameters for its generation.

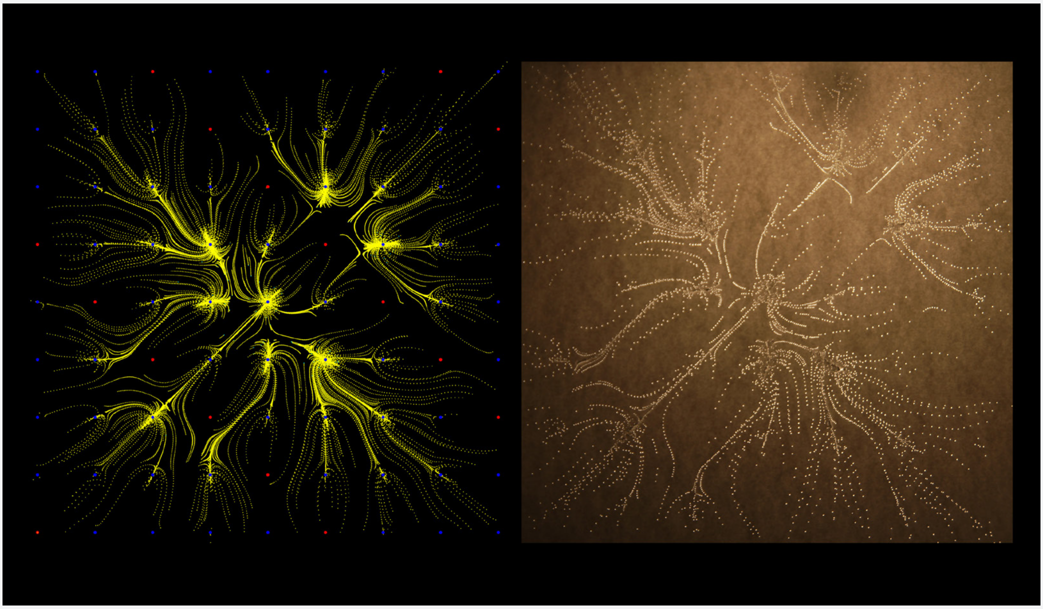
During the process of converting the pattern to a set of points that could be used by the robot and that represent the designer's intentions, a set of additional parameters had to be introduced to the code such as: Z-values for the robot to lift after each point or at the end of the lines so they are not continuous and indistinguishable, checking reachability to all the points, height and rotations of the designed end effector, analysis of the number of points in the digital pattern versus the necessary ones in the physical world to optimise machining time, speed of the robot, and more. The students were able to achieve this via intensive collaborative working in the studio that allowed rapid generation of patterns, immediate access to the robot for testing, and continuous access to manual jogging of the robot to understand its behaviour with regular tutor support. During the 5-day production phase of the workshop, 14 students generated over 30 physical drawings in a continuous evolution of forms. The final outcome allowed students to explore forms of design and creation using an industrial robotic arm, to understand the potentials of the machine and to realize that a series of parameters has to be considered from the early stages to have a successful, strong, direct connection between design parameters and physical output.



▲ **Figure 7** Setup for Robotic drawing of the generated patterns



▲ **Figure 8** Photographs of robotic drawings from generative patterns.



▲ **Figure 9** Photographs of stippled robotic drawings from generative patterns.
All figures from AADRL, 2015. Instructing Machines workshop.

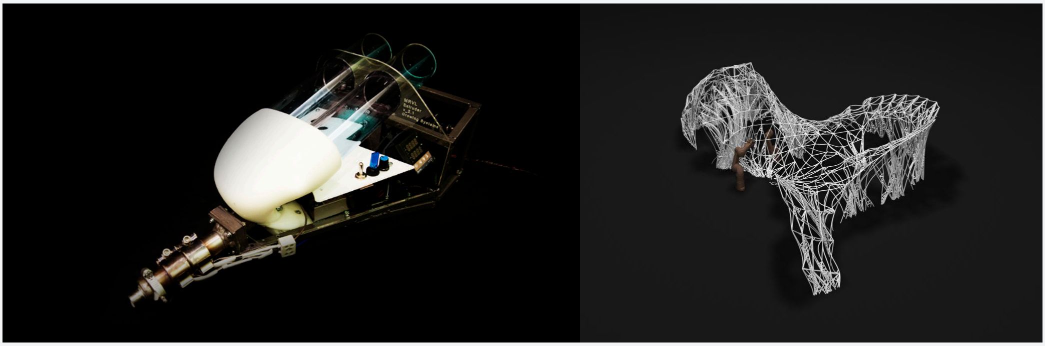


Figure 10 Left: custom-made end-effector. Right: Generative design system based on multi-agent behaviour

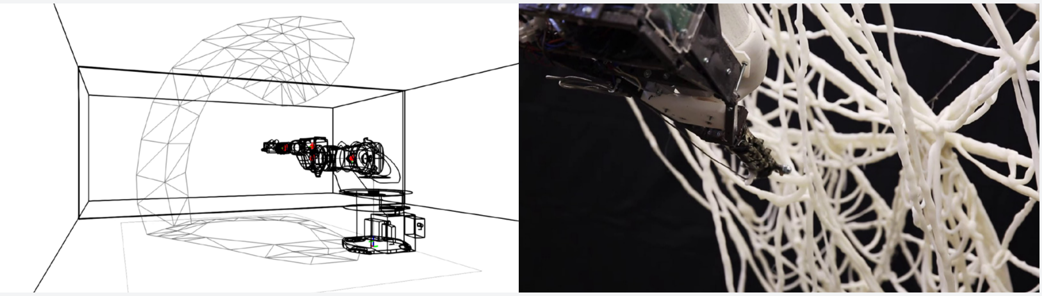
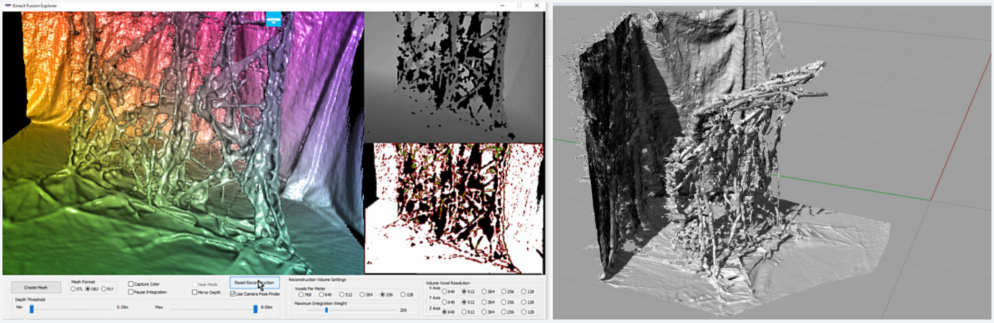


Figure 11 Left: Initial path setup. Right: Extrusion detail



Kinect Fusion Explorer

Create Mesh

Mesh Format: ○ STL ● OBJ ○ PLY

☐ Capture Color

☐ Pause Integration

☐ Near Mode

☐ Mirror Depth

Reset Reconstruction

☑ Use Camera Pose Finder

Depth Threshold: Min 0.35m, Max 8.00m

Reconstruction Volume Settings

Voxels Per Meter: ○ 768 ○ 640 ○ 512 ○ 384 ● 256 ○ 128

Maximum Integration Weight: 200

Volume Voxel Resolution

X Axis: ○ 640 ● 512 ○ 384 ○ 256 ○ 128

Y Axis: ○ 640 ● 512 ○ 384 ○ 256 ○ 128

Z Axis: ● 640 ○ 512 ○ 384 ○ 256 ○ 128

Figure 12 3D scanning using Kinect for robotic path recalculation and for calibration between physical and digital models.

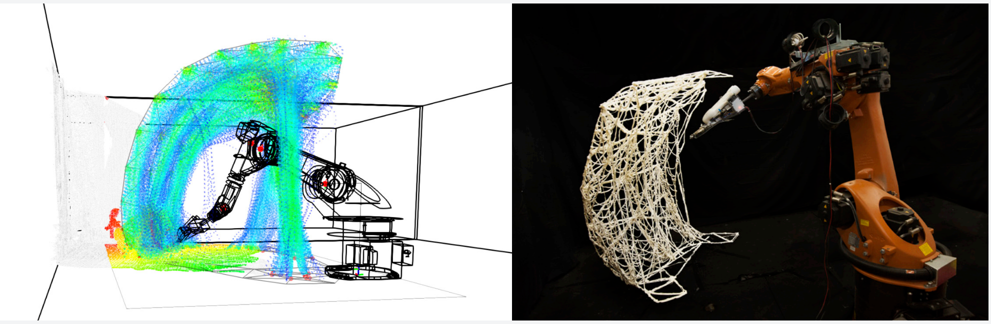


Figure 13 Left: re-computed tool paths based on deposited material. Right: Built prototype of spatially extruded polymorph plastic. 1.8m tall. All Figures from Team MRVL, Studio Bhooshan, AADRL 2015

7.2 MRVL Plastic Spatial Printing:

A collaboration with Studio Bhooshan from the Architectural Association, Design Research Laboratory. M.Arch (AADRL), London, UK.

MRVL is a team of 4 students from Studio Bhooshan at the AADRL. In December 2015 during the final stages of their 16-month Masters program, they worked with the first author as an observer and robot consultant to their fabrication process. The focus of the design lab is in developing prototypical construction methods that allow describing, evaluating, and searching for the right designs using robotic industrial arms (Architectural Association 2015). The team designed and developed a custom-made end effector for a 6-axis industrial robot to spatially extrude polymorph plastic in a collaborative fabrication process. Polymorph plastic traditionally comes in granules that look like small beads.

The team developed a design system based on topology optimisation and multi-agent generative design principles. The system, following the rules established by the designer, generates different configurations of architectural space, providing the positions of main and secondary structural members. These are then transformed into paths for the robot to extrude / deposit plastic. The purpose-built end-effector heats the pellets to 90 degrees before starting extrusion and has sensor controls to prevent overheating.

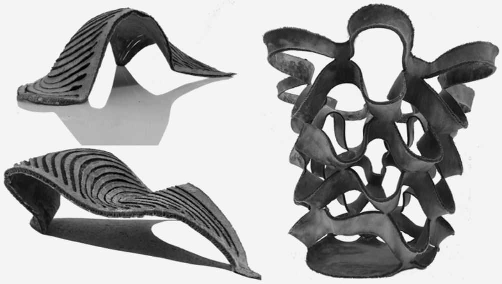
The specific characteristics of the material make it shrink slightly after extrusion. This, combined with the precision of the robotic arm, which cannot adjust on its own to the varying shrinkage, necessitates the introduction of a robotic vision system in which each path is scanned after deposition. Information obtained from the 3D scan is then fed back to the original design model in order to calibrate the digital and the physical, analyse the geometry, and re-compute the next extrusion path to ensure that all structural members are connected with each other. A system in which the robot becomes an agent responding to previously extruded plastic is created.

The process requires extremely active participation on the part of the designer during the fabrication stage. As opposed to traditional robotic fabrication processes, in which all the instructions are sent to the robot at the beginning, the setup feedback loop requires the robot to ask the designer after each path where to go next. For each path, the robot needs to keep the form-optimisation while avoiding already deposited material. As the form builds up, it becomes more densified, so the robot's awareness of its environment is crucial. A semi-autonomous system is created, in which the robot can keep to the next path as per its analysis based on the scanned information and re-computation of the system, or the designer can provide a different solution based on his or her qualitative analysis and overall design intent. As the design adapts to the environment and responds to previously extruded plastic, it is continuously changing during the fabrication process. The final outcome can have several degrees of variation from the initial input, hence the importance of the designer's active presence during the process to control variation and adapt both the digital model and the physical model through the robot. During the 4-day production phase at the Welsh School of Architecture, the team built a 1.8-meter-tall prototype with a weight of 25kg. The robot printing time was 12 hours.

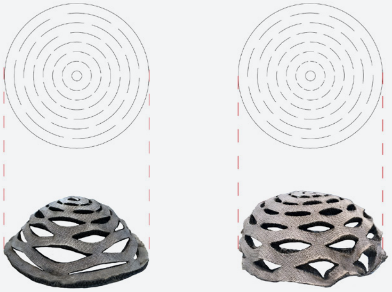
7.3 Pop-Up Concrete:

On-going research project developed by the author at the Welsh School of Architecture.

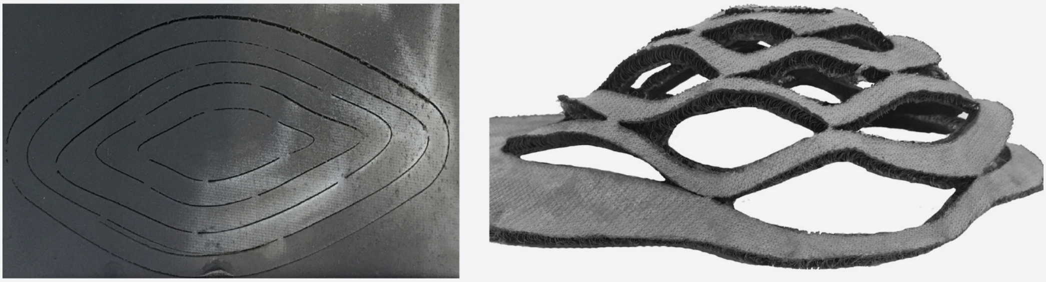
Flat packed, pop-up concrete structures are explored as a means to create a flexible and adaptable fabrication system for the creation of thin-shell, medium-span complex concrete



▲ **Figure 14** A vocabulary of pop-up structures is starting to develop, as a result of the design process



▲ **Figure 16** Changes to the cut and joint pattern with boundary conditions and relaxation constant show different results after inflation

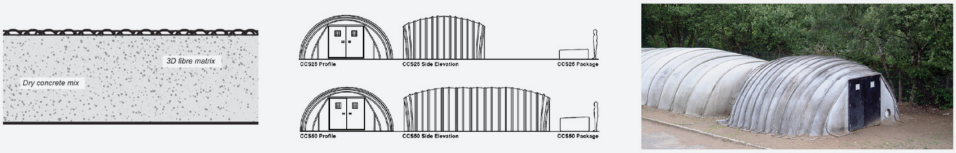


▲ **Figure 15** Left: 2D pattern laser cut in concrete canvas. Right: Popped – up concrete canvas shell prototype

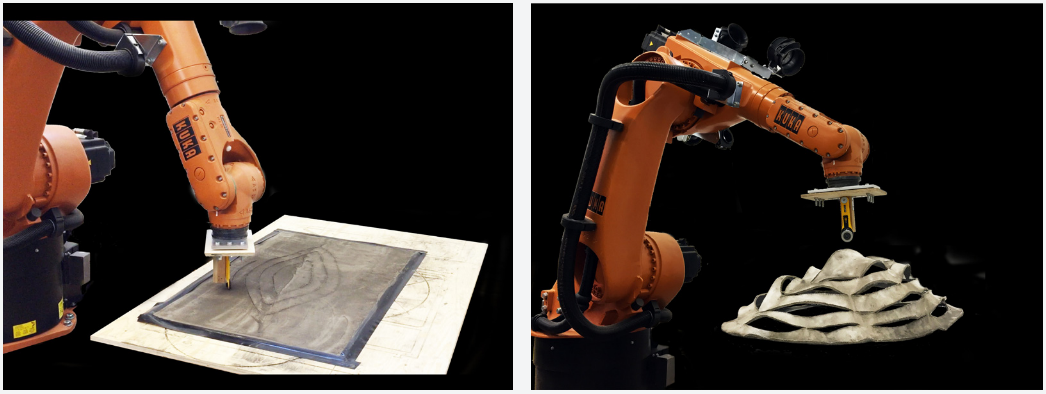
structures, furniture, and complex leave-in formwork for larger structures. For this process, Concrete Canvas, a new material technology, is explored due to its hybrid characteristics that blend fabric and thin-shell tectonics. The focus of the research is to develop novel construction systems that integrate with the current robotic and architectural discourse. The digital workflow includes: pattern design; digital simulation; on-site cutting and inflation through a collaborative, iterative, material feedback loop; structural analysis; and hydration of the final shape. It allows the designer to manipulate concrete structures on-site, as informed by structural analysis, designer input, and their own choices.

The popped-up geometries are based on a parametric system of 2D cutting patterns performed in 'concrete canvas'. The 2D patterns transform into extended 3D surfaces by lateral buckling induced by spatially non-uniform growth during the phase-changing period of the material. The system setup is initially done both physically and digitally, so that when the units pop up they inform and calibrate each other through an iterative feedback loop. A pattern gets embedded in the material so that, when it pops up, it is capable of a range of configurations that are structurally stable while also achieving qualitative architectural effects. Fabrication, in this system, comes from embedding transformative capacities in the material, rather than from transferring the form directly from the computer into the material as in traditional unidirectional fabrication processes.

Beyond the optimization criteria and parametric setup, the system focuses on collaborative design as a way to approach material exploration through robots. Typically, the outcomes of a fabrication process are predetermined. However, the introduction of a 2D cutting



▲ **Figure 17** Left: Concrete canvas section. Middle: Typical deployment sequence. Right: Shelter structure. Source www.concretecanvas.com



▲ **Figure 18** Top: Setup and end effector for robotic cutting of concrete-impregnated fabric. Bottom: 1.0x0.7x0.7 popped-up prototype.

pattern within a concrete phase-changing material system over a pop-up process allows for several configurations to be created through a collaborative design and fabrication process. The feedback loop between designer, material, and robotic production creates negotiation opportunities that result in a rich and complex design process with many intelligences: human, the algorithms embedded in the design, and the material.

Concrete Canvas, as a material, allows for experimenting with new uses for concrete. It is composed of a layer of dry cement with its reinforcement impregnated between two sheets of fabric. In its dry state the material can be formed and worked as malleably as fabric, but when hydrated it becomes very rigid, acquiring the stable properties of concrete. Given this duality, the behaviour of the material is probable, but not certain. This characteristic allows one to assess the structural influence of the patterns of cuts and joints and the effects of its variations during the pop-up process. The system uses inflation to pop up into a surface. Once a satisfactory shape is achieved, the concrete is hydrated, allowing it to cure and become structurally rigid.

Using new digitisation technologies, the popped up shape is scanned and taken back to the computer for structural analysis and calibration with the digital simulation and for 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 hydrated and left to settle for 24 hours. A feedback loop between the digital and the material is created and continuously updated during the form-finding and form-making processes. The aim of the system is to provide a production technique for the quick

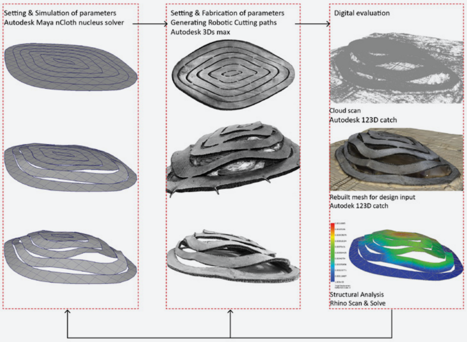


Figure 19 Diagram showing the workflow set out and feedback loop

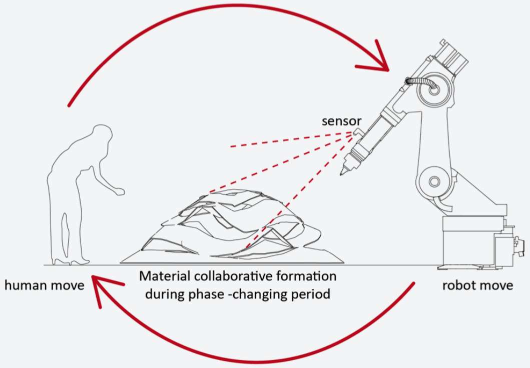


Figure 20 Designer-robot -material negotiations during the formation, or pop-up process, of the material

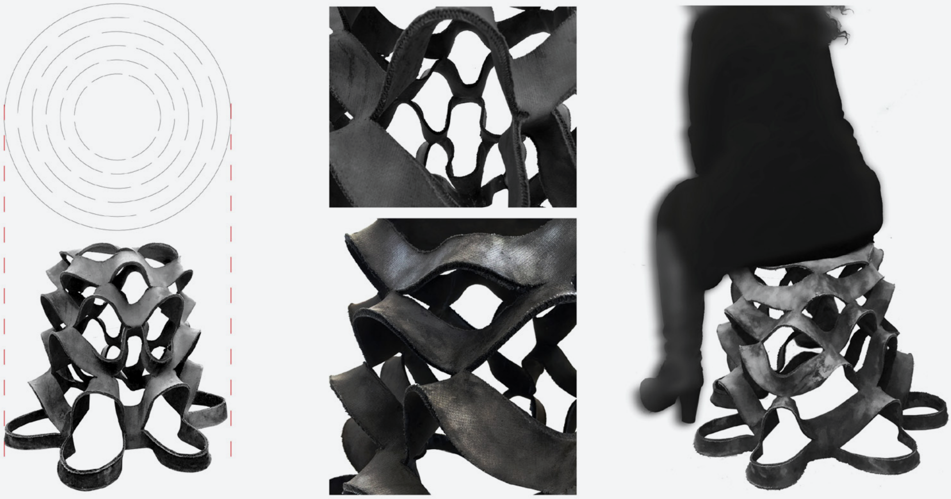


Figure 21 Left: 2D pattern and resultant 3D geometry. Middle: Concrete details. Right: Live load testing of prototype

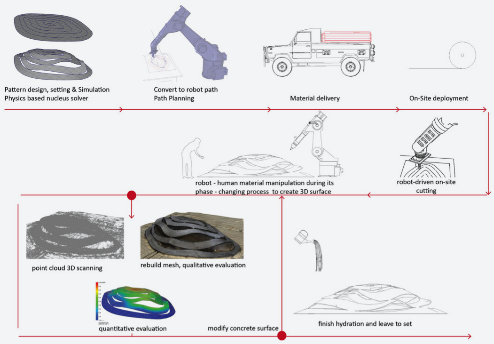


Figure 22 Envisioned fabrication scenario, including path planning workflow and feedback loop

deployment of shell structures, where modelling, analysis, and fabrication are integrated. Form in this process emerges as a result of a negotiation amongst structural, material and design constraints.

The generation of pop-up structures is not random, but caused by set boundary conditions of the embedded cut and joint pattern, and follows precise physical principles during its pop-up. Through the feedback loop and with defined boundary conditions, the results can indirectly be controlled and emergent shapes can be created by stopping the process at any point in time during the pop-up phase of the concrete. 3D pop-up geometries can achieve a space-enclosing surface faster than 3D printed ones.

In this case, as opposed to that of the previous one, the designer constrains the possibilities of the system through the design of the cutting pattern and the properties of the concrete fabric. During the pop-up process, decisions can be made that favour different final configurations. This variation is bracketed to the realm of possibilities allowed by each cutting pattern initially defined and simulated by the designer. This kind of approach changes the role of the architect to that of an editor of constraints and a designer of a system through the material and the machine, rather than that of a designer of the final product.

8. DISCUSSION

The case studies show how using the symbiotic agencies of the robot, the designer and the material allows us to explore opportunities to create new aesthetic languages for our built environment. The interaction between the robot and the designer can happen at different stages of the design, from very early phases as in the first case study, up to the final delivery of the design, or during its construction as shown with the pop-up concrete and the plastic deposition examples. In these last two cases the iterative fabrication process leads to a sentient material that engages, through the robot, in a design dialogue with the architect.

Experimenting with materials as per case studies 2 and 3 proved to be an immersive and fascinating field very easy to get lost in (Hale 2013). Keeping in mind that the main objective is searching for new modes of practice and connections between the different agencies allows us to speculate 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, to their designs. This shift represents challenges for architecture that open new formal and epistemic opportunities (Witt 2010). In these envisaged scenarios, architects are no longer designing buildings and its works 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.

9. CONCLUSIONS

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 those which painters and sculptors have enjoyed, yet with the precise digital control. This control is achieved through the use of sensors and vision technologies guided by the machine. The exactitude of variation during the materialisation process is new to the architectural designer. However, concrete, larger-scale industrial applications of robotics in architecture are still missing.

Robots support a new multidisciplinary approach to design, encouraging architects to work directly from early stages with engineers, materials scientists, and electric engineers providing a more holistic approach to construction. They allow architects to mix craft and tools in an intellectually meaningful way, creating a trinity of material, technology, and form (Lynn 2008). The usage of a robot, its limitations and constraints has to be considered from the beginning. This requires the incorporation of specific thinking during the generative design stages, as shown through the case studies. However, robots are only one part of the construction process, and in some cases the robotic part can further complicate downstream and upstream processes. Robotic fabrication needs to be able to handle a continuum of inputs and outputs feeding into each other. The methods in which robotic processes integrate with the rest of the construction site, and in which robot-human choreographies can be measured and adapted to the different routines needed during the on-site life of a project, are enormous areas for exploration.

These case studies demonstrate a number of proof-of-concept human-robot collaborations for robotic-aided fabrication. This design agenda involves not only human-robot interaction, but also robot-robot interaction and the development of a range of robotic and multi-robotic choreographies and their orchestration. Robotic-aided fabrication holds the potential for rethinking the role of the architect in the design and fabrications process. It allows for the creation of a new professional role for the architect that combines critical thinking whilst taking advantage of new tools and agencies interacting collaboratively to create greater designs that would be nearly impossible otherwise. In its current status, it encourages performative dances of agency without a defined centre.

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