Digital Materialization: Additive and Robotical Manufacturing with Clay and Silicone

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Through the use of algorithmic design methods and an ever growing variety of digital fabrication tools the complexity of process in the architectural discipline seems to be increasing. As this statement might apply to a variety of different areas of computational design and process management, this perceived growing complexity does not have to be viewed as unnecessary complication of design processes, if palpable and justifiable benefits occur. This paper intends to analyse and investigate the potential arising from digital tools of fabrication, specifically robots and 3D printers, and from open source platforms on exploring and managing complexity while enabling both simplicity of process and simplicity of implementation through emerging open source cultures. Building on this assumptions, this paper explores the professional possibilities generated the implementation of robotics as part of the academic curriculum. The theoretical concept of Machinecraft will be introduced and showcased on two research project, both focussing on advanced digital tools, additive manufacturing and machine engineering. Please write your abstract here by clicking this paragraph.

Keywords: Additive Manufacturing, 3D Printing, Robotics, Digital Fabrication, Open Source, Architectural Education

INTRODUCTION

This paper explores the possibility of developing an awareness and understanding of the new and combined role robotics and open source platforms occupy in the architectural process and in interdisciplinary academic teaching, from the stage of defining the project's framework to the stage of digital fabrication. This issue will be addressed on two levels of discourse. While the first level discusses the theoretical-philosophical framework behind the architectural integration of machines, specifically robots, the second investigates the resulting methodological implications on two applied research projects, one developed at the Edinburgh School of Architecture and Landscape Architecture at the University of Edinburgh and the second at the Institute for Advanced Architecture of Catalonia in Barcelona. The attempt to redefine the status of the machine in general, and specifically of the robot, seeks to illustrate the robot as an active design agent, capable of influencing and redefining established processes in architecture. Simultaneously the analysis focuses on develop-
ing an understanding of the role of computer aided design and digital fabrication in architectural education and to showcase a set of approaches of how to make use of open source platforms and ways in which these new territories can be implemented in the academic context. As a conclusion, this paper will investigate on the relevance of computation, digital fabrication and open source platforms for the architectural discipline and its professional identity and how these enable future architects and researchers to access other disciplinary fields with the outcome of advancing and adding complexity to the own discipline. It is of high importance to analyse and investigate the potential arising from digital tools and open source platforms on both exploring and managing complexity, while enabling both simplicity of process and simplicity of implementation through the earlier mentioned open source cultures.

THEORETICAL FRAMEWORK

In order to redefine the importance and relevance of the machine, including self-developed or manipulated machines as 3D printers or robots, for the whole of the design and fabrication processes in the discipline of architecture, the author presents the theoretical concept of machinecraft. The concept of machinecraft intends to combine the two operational ways which are being represented by its word composition. Machinecraft describes the process of developing a fabrication strategy which satisfies the requirements of design, material and machine parameters. It relies on a closed informational circuit in which design, material and machine information constantly complement and influence each other. Machinecraft addresses the ability to extend the area of control over the machine, just like a craftsman controls his tools, this meaning to be able to manipulate the technical, mechanical configuration of a machine, in order to attune it to material and design requirements. This manipulation can be done in two ways. If in possession of advanced programming and engineering skills, the change of the machine configuration can be done actively by the user, in this case the architect. Through the means of open source platforms these technical interventions and manipulations are considerably simplified for the user and offer a direct way of handling complexity through simplified means. In the second case of highly complex systems, the adaptation of machine configuration will be achieved by collaborating with mechanical engineers or the machine developers and giving indications to how and why the mechanistic operating mode should be changed according to project specific needs. This last step can be only done, if a preliminary examination and understanding of the operational system has been done, so that the implications which result from conducted changes consort with the desired outcome. (Nan 2015.) The concept of machinecraft is rooted in the assumption, that just as architects gradually engage in the customisation of design software through scripting, in the development of customised materials or material systems (Menges 2008) in order to increase the optimisation and effectiveness of both design and making, the same should be valid for their engagement with customising themselves machines. The access to and manipulation of mechanical systems such as robots, CNC machines, 3D Printers and many others, from a software and hardware point of view, is today radically simplified through the access to open source platforms, such as Processing, Arduino or even Grasshopper, to just name a few. These type of machine systems were previously considered as highly complex and complicated so that a direct manipulation in terms of their software-hardware through the architect was highly improbable. Throughout the Digital Turn and the advancement of the open source cultures these realities have changed. Because of the emerging open source culture the architectural design but also increasingly the fabrication processes and strategies can be seen as network-driven activities, based on an inherent collaborative practice. (Ratti 2015.) The generated effect consists of making complexity accessible and transforming it into simplicity, in the sense that networks of information or mechanical systems, previously highly discipline specific, become accessible to
architects and free to manipulate. This leads to overcoming design and machine limitations, thus allowing the architect new degrees of disciplinary freedom. This new type of interaction between the architect and the machine can be simultaneously seen as a strong catalyst for future cross disciplinary interactions. Open source offers the possibility to manage and handle complexity in new ways by permitting and enabling active manipulation of systems.

RESEARCH STUDIES
The previously described theoretical approaches and constructs will be exemplified and demonstrated on two applied case studies, both focusing on additive manufacturing and advanced digital tools, but which show different scales of implementation.

Research Study 01: From Fabric-Cast Concrete to Silicone 3D Printing
Context. The following presented research project was developed during the MSc Material Practice 2014/15 programme at the University of Edinburgh. The research showcases an investigation into digital material experimentation and simultaneously features the relationship between aspects of the digital craft and tool development for digital fabrication. During the first research phase, experiments were undertaken with fabric-cast concrete and 3D printing with silicone. These initial investigations led to the development of a self built ceramic and silicone 3D printer and ultimately generated prototypes of customised medical braces and gloves. Additive manufacturing and textiles can be seen as the main line of research which continuously goes through all of the further described research phases. The educational value of integrating advanced digital fabrication, specifically additive manufacturing, as part of an academic interdisciplinary curriculum is being showcased.

Lines of investigation.
Fabric-Cast Concrete and Silicone 3D Printing. Initially work was undertaken looking at textile formwork for concrete structures as a viable alternative to conventional formwork, commonly fabricated out of wood. The use of textile formwork represents a major advantage when dealing with complex geometries, for instance based on single or double curvature as it does not require any additional and material-intensive scaffolding or moulds. As an output of this first stage, a series of fabric-cast concrete columns resulted. This process offered the starting point for understanding textile material behaviour as a tool for form control and generation. As a next step, a series of experiments followed which investigated the impact of 3D printing and patterning directly on textile formwork and fabric-cast concrete. The material interaction between concrete and 3D printed patterns out of silicone was analysed through a series of material iterations. Although the silicone alters how the fabric stretches in response to the wet concrete, no major material difficulties were encountered in terms of the casting process and or removal of the silicone pattern design. Through the interaction between concrete and silicone, an untypical hybrid material system, a new type of unexpected material aesthetic was generated. Being a soft, flexible and water-repellent material, the silicone allowed for precise detail to be taken by the surface. Unlike conventional moulds and formwork, the silicone can be easily removed, the ease and low cost of each print meaning that each formwork is essentially disposable. Rather than the costly and time consuming method of cre-
ating castings, or stitching objects into the fabric, the silicone alters both the structure of the form as well as detailed surface finish.

**Ceramic and Silicone 3D Printing.** These initial experimentations with textile formwork and 3D printed patterns on the fabric evolved into an investigation of additive manufacturing techniques firstly with clay and as a second step with silicon on textiles. For these purposes a self-built, low cost 3D printer was developed. As starting point and technical instruction resource for the construction of the 3D printer, the open source kits for a 3D Delta Printer for ceramics provided by the researchers Jonathan Keep and Dries Verbruggen were used. The developed low cost Delta Printer is suited to printing taller objects in clay due to the stationary circular base and tall build volume, compared to a Cartesian Printer. It is only through the 'free revealing' and open source development that this type of cross-disciplinary project is accessible and manageable for architectural students. Despite beginning the project with minimal experience of 3D printing from the student side, as a 'user innovator' the internet allows 'access to the rich libraries of modifiable innovations and innovation components that have been placed into the public domain' (Von Hippel 2005, 121). This new type of emerging 'user-innovator' is characterised by a movement between roles, in this between architectural designer to product engineer, which inherently enables a revised approach towards the dynamics between design and fabrication process. A central theme that developed throughout this research was the value of the low cost printer that evolves to the specific requirements of a material. The advantage of manipulating a hacked open source 3D printer lies within the possibility of customising extruder and nozzle for the use of a well defined range of diverse materials, in this case clay, porcelain and silicone, offering thus a greater flexibility in contrast to commercial printers and so is open to elements of disruptive innovation. There is currently no commercial printer that would allow simultaneous experimentation with this material range, or provide platforms for different substrates. The experiments with ceramic 3D printing focused on understanding the parameters of correlation between the material and the machine. A wider range of materials for extrusion has been explored, from clay to terracotta and porcelain, showcasing different extrusion behaviours. In order to obtain an optimal extrusion result, the following parameters had to be considered: extrusion rate, extrusion speed, material viscosity, nozzle type and material depositing strategy. The focus of this work lies in understanding how to manipulate and control the ceramic 3D printer in order to then further advance to developing a material depositing strategy for medical hand braces with locally deposited silicone through 3D printing.

**Medical gloves and compression braces.** A key aim that developed during the further line of investigation was to find relevant applications for the low-cost method of printing silicone onto textiles. This
evolved into the creation of customised compression braces for medical purpose, by making use of low cost materials and accessible additive manufacturing technology. Initial printing tests were executed with latex and silicon. The latter was adopted for further experiments due to its homogeneity, which corresponds to industrial standards, the more flexible extrusion process, easy availability and low cost of material. The main design principles for the compression braces and gloves relies on investigating the relationship between patterning and stretching. Using pattern design to influence the compression and stretching behaviour of textiles can be of high relevance for the medical development in order to enhance ergonomic features of support braces or to customise protheses. The research development was done through multiple digital and material iterations, by simultaneously correlating material behaviour, pattern geometry, fabrication process and machine. Through the parallel development of the material, digital and mechanical customised flexible prototypes were developed. In order to obtain working prototypes a precise calibration of specially material and machine parameters was necessary, thus enabling the designer or architect to obtain an increased control over both design and fabrication process.

**Software and Hardware.** For this experimental series an existing plastic FDM printer was hacked and technically upgraded. A new RAMPs board was installed as well as a new printhead developed to suit the silicone. The main effort was put into controlling and manipulating the extrusion rate and flow of the silicon, based on previous experience with ceramic 3D printing. This involved developing an extruder to mechanically dispense the silicone straight from the cartridge, having previously explored but realised limitations of printing with air pressure and solenoid valve allowing precise control of extrusion between movements. Rather than developing a separate reservoir of silicone, the extruder was designed around a standard 300ml sealant cartridge. The extruder developed within the Engineering FabLab
consisted of a mechanical screw, that forced the silicone through a PTFE tube to a nozzle mounted onto the printhead platform. The digital workflow consisted of designing the differentiated patterning, so custom print paths, to enable the creation of silicone objects impossible with standard slicing software. The modelling was based in Rhino and Grasshopper was used to vary the density of the pathways over a cylindrical form, originally scan of an arm, and so influence and manipulate the areas of compression. This output was then turned into a single path, to enable consistent, clean printing. As the mechanical extruder of the printer did not have the capability to consistently retract between movements, it was necessary for each layer of the object to be printed in a single path. This printing strategy had a significant impact on the process of designing the final prototypes. Further experimentation was done with an XBox Kinect 360 scanner, and free software to scan elements of the body in order to increase the ergonomics of the braces. As a final step Silkworm, a plugin for Grasshopper, was used for generating the G-code. The workflow of scanning, manipulation and printing led to a series of combined digital simulations and physical experiments, in order to obtain a higher design refinement.

Conclusion. Through engaging with textile formwork to building a 3D printer and developing 3D printed pattern designs for textiles, a profound understanding was gained of related software, hardware and the material behaviour. During this experimental series a tacit knowledge of the process was developed. The theorist Richard Sennet describes 'tacit knowledge' as the implicit experiential understanding of a process or material, '...knowledge that has become so self-evident and habitual that it seems just natural' (Sennet 2008, 183). From an educational point of view the tacit knowledge represents an emerging set of skills which are typical for craftsmanship and can be only developed and accessed through a hands on approach. This applies not only to the traditional context of craft, but also to the digital context. By being directly involved in the mechanical assembly of a 3D printer an experience is being generated which is of significant educational value and confirms the concept of machinecraft: the architect actively engaging in the technological development of the chosen digital fabrication tools in order to adapt them to specific project demands and to thus overcome machine limitations. This type of consequential emerging knowledge through direct process involvement can be also defined as 'sticky' or 'local' information. The American economist Eric von Hippel considers that this 'information used in technical problem solving is costly to acquire, transfer, and use in a new location' (Von Hippel 1994, 429). This is the information immediately available to the user--innovator, that is used to further development of the product or process to suit immediate needs. This generates a valuable educational insight as the interdependence between design, material, process strategy and tool becomes apparent to the student.

Research Study 02: Minibuilders
Context and Concept. Constructing to the previous case study which focuses on small-scale prototyping and on the integration of new digital cultures as part of a revised academic curriculum, the following project creates a change of scale, as it engages with on-site fabrication strategies. The case study at issue, bearing the name Minibuilders, was developed as a robotic research conducted as a group project at the Institute for Advanced Architecture of Catalonia in Barcelona. Minibuilders is a project which deals with architectural robotics and additive manufacturing for
big-scale structures. The case study illustrates the development of a robotic fabrication strategy based on the use of a multiple robotic system which uses a material distribution system similar to the current 3D-printing, but adapted to on-site fabrication. The most relevant aspect of this research lies within the fact that instead of choosing to work with industrial robot arms for the construction of architectural elements such as walls or columns, a reversed approach was taken. Using robotic arms or portal 3D printers for construction is based on the idea of using oversized tools, so heavy machinery, in order to build equally big structures. Operating with such tools implicates a series of considerable disadvantages for on-site fabrication:

- Inflexibility due to the physical size of the robot.
- A limited area of reach depending on the length of the robot arm or the size of the 3D printer.
- Reduced mobility, as industrial robot arms move on trails and are not able to move independently across space.
- Building limitation through the size of the printer itself. In case of portal printers, the structure to be erected has to always be smaller than the machine itself, just as in the case of a commercial 3D printer.
- Heavyweight for on site construction, as the additional load of the robotic arm has to be considered during the planning and the organisation of the construction phase.

The Robots. Taking these criteria into consideration, the here developed strategy for on-site printing is predicated on the development of a series of mobile robots, which can act independently from one another and thus fulfil separate functional demands. The three developed robots with their built-in technology represent a hybrid between robotics and 3D printing: while the mechanic specifications corresponds to the ones of robots, the integrated material deposition system correlates in its procedural features to the functioning of 3D printers. The drafted strategy relies on dividing the on-site construction processes into three phases, according to functional necessities. The three phases are consecutive and each correlates with the use of a different robot. The first robot, the foundation robot, to come into operation is responsible for raising up the first ten to fifteen layers which form the foundation of the future structure. Subsequently, after the foundation is finished, the second robot continues depositing the following layers and finalises the design. Whereas the foundation robot is capable of moving on the ground, the second robot, named grip robot, needs to be manually positioned on top of the finished foundation layers. According to the task it needs to fulfil, the grip robot is designed as a type of climber robot. After being placed in its position, the grip robot continues with the successive deposition of the layers. The grip robot is the robot which completes the form and which is responsible for the main construction task. As both the foundation and the grip robot deposit horizontal layers, any resulting structure, independent of its shape, will exhibit a restricted structural stability. Naturally, the cause of this lies in the absence of vertical reinforcement. In order to counteract this effect and to offer an increased structural stability, vertical layers along the horizontal ones must be added. Concluding, the third phase seeks to address this problem and deals with the construction of the earlier mentioned reinforcement layers. This stage is based on the utilisation of the vacuum robot which is designed for ensuring a vertical motion. As indicated by its name, the robot creates a vacuum between himself and the surface of the structure in order to be able to advance vertically. The robot moves along the structure, by following predefined paths. These pathways originate from a previous, detailed structural analysis of the design. Grasshopper and the plug-in Karamba were used in order to generate this information. After the completion of this last layer, design and construction process can be considered as finalised.
Material System. The used material for the extrusion is a composite material based on marble powder and a two-components resin system. The two component resin system was added as to accelerate the curing time of the extruded layers in order to facilitate a smooth and stable movement of the robots on top of the deposited material layers. A series of parallel physical and digital experiments was done so that the right mixing ratio to obtain an optimal viscosity and texture of the material for the extrusion could be determined. The development of the material, the extrusion nozzle and the extruder happened in parallel, as they represent correlated and interdependent parameters. Material, machine and building data thus form a reciprocal informative circuit. This type of approach generates a new level of complexity regarding the architectural input and the levels of intervention, control and manipulation through the architect. Considering that the here showcased study was handled as a proof of concept, only a limited amount of exploration was invested in the development of the composite material itself in terms of its fitness for the construction industry. Considering the addition of the two-component resin system the material cannot be considered as fully sustainable or ecological.

Future Investigations. The described printing and construction strategy represents a proof of concept to showcase that small robots may be more appropriate to be used to print large-scale structures on site, rather than industrial robot arms, which are more suited for fabrication processes along an assembly line. The refinement of the robots in terms of their moving mechanisms, the development of a sustainable material system, the detailing of the extrusion nozzle and their further specialisation regarding the tasks they fulfil may represent main investigation objectives for future research. This project showcases the importance of architects being directly involved in the development of actual fabrication strategies, in terms of machine development and process restructuring and organisation.

CONCLUSIONS
The implications of the architect as a robotic inventor and the incorporation of machine, fabrication and material parameters in the architectural process are evidenced. Through the integration of self-developed robotic devices as autonomous design agents a new understanding of digital fabrication, the construction site as a robotic environment and
the crafts nature of the architectural discipline may arise. Through the means of open source platforms and programming new areas of competence, such as product engineering, material development and mechanical engineering, but also influence can be accessed by designers and architects alike. The importance of mastering these digital tools goes beyond just expanding a digital skill-set, but it demonstrates the disciplinary relevance of advancing in parallel design and fabrication strategies, which are intrinsically connected to one another. The emerging digital tools of design and fabrication, specially the generation of new desktop fabrication tools such as 3D printers, laser cutters or 3D scanners in combination with the developing open source culture have the potential to revolutionise and democratise the discipline and thus initiate a new industrial revolution. (Anderson 2012) Digital fabrication practices have the potential to expand the control of the maker, in this case architects and designers, over the design process and to overcome machine limitations. They can be seen as extensions of the traditional processes, adding an element of manageable complexity, so that the parallel development of hardware and software can sustain an intelligent network development of design, material, fabrication and machine.

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formation on the individual members of the research team, the extended academic support, sponsorship and collaborators can be viewed on the official webpage dedicated to this project.

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