A NEW MACHINECRAFT. ARCHITECTURAL ROBOTS

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Abstract. The topic of this paper concentrates on robots and their new role in the architectural process from the early stage of conceptualization to the final stage of its materialization. By presenting a theoretical framework and an applied case study, this paper tries to initiate the discussion of redefining the status of the robotic machine in architecture. Besides being a regular tool among other digital fabrication tools, the robot and the ability of the architect to technically manipulate them, bears the potential of further reconnecting and intertwining the process behind design and fabrication. Operational and structural processes are being modified and points of focus shifted. Digital design connected by customized robotic machines to digital fabrication has the capability to result in a new type of architecture.

Keywords. Machinecraft; robotic printing; robotic fabrication; construction strategy.

1. Introduction

This paper intends to develop an understanding of the new role robotic machines or systems occupy in the architectural process from the early stage of conceptualization to the final stage of its materialization. This issue will be addressed on two levels of discourse. While the first level discusses the theoretical-philosophical framework behind the architectural integration of robots, the second investigates the resulting methodological implications on an applied research project. The main aim is to provide a framework for redefining the status of the robotic machine in architecture. 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, which influences the whole architectural process.
2. Theoretical framework

The last 25 years of architectural development have been significantly influenced by the profound digitalization of the discipline. At the beginning of the digital turn the main fascination with the new digital tools was primarily focusing on digitally influencing and controlling form generation. Digital fabrication tools were not completely excluded from the agenda of interest, but only after the first wave of form generation exuberance faded away, architects turned their focused attention also towards the means of digital fabrication and production. During this time span, the interest moved from multi-axial milling machines to laser cutters then to 3D-printers and reaching finally the robotic arms. A look at academic research pavilions suffices to read this development. The academic student pavilions mirror best the implementation order of the digital fabrication tools and act as an indicator for the shift of the technological attention allocated by professionals.

The implementation of the digital tools in the two areas of form generation and the making of form led to vast polemical discussions over the impact and the relevance the new processes will have over time. During these debates a multitude of paradigm shifts have been evoked, the shift from mass production to mass customization, the shift from the analog to the digital just to mention a few. But leaving aesthetic and form orientated debates aside and concentrating on the constructive substance of architecture, the most relevant shift was probably “the paradigm shift in the production conditions of architecture” (Gramazio et al, 2014) caused by the new generation of digital fabrication tools. Founding the first worldwide architectural fabrication laboratory to include robots, Gramazio and Kohler argue that the division between the design process, understood as an intellectual act, and the fabrication process will be easily overcome through the use of robots by architects, as robots directly involve the architect to all processes (Gramazio et al, 2014). of It is important to not only concentrate on the use of these technologies and their implementation in the fabrication of architectural elements, but also to observe the changes which deviate, on an operational and structural level, from the use of robotic machines as direct tools of the architect.

One of the biggest advantages of the insertion of the robot in the architectural practice is the omission of an intermediary agent between architect and the fabrication tool. The architect himself is in control of the robot, by defining a set of instructions. By observing the way of evolution of today’s robots and their integration in the design, material and constructive processes, the concept of architecture machines (Negroponte, 1969) seems to be reactivated. The variability and variation of the design and thus of the design series is a topic which has been often evoked in architecture (Lynn, 1998). Digital fab-
Fabrication tools and mass customization guarantee the unproblematic buildability of various design series. The variability of the machine according to a specific project would represent the next step. A move towards this direction was already taken by using robotic arms. A second approach consists in leaving the idea of the non-specific robotic arm aside and instead developing for every project customizable robots or machines, as project specific tools, which are able to react specifically to the multifarious constraints of the project. This is where the self-developed term machine craft ties in. Machinecraft describes the ability of the architect to be involved in machine development, adapting and customizing machines according to design and material requirements. Thus, besides controlling the design, material and informational processes, the architect would be also in charge of designing machine devices and the corresponding robotic strategies. Apart from being the operator of the machine, he would also be to a certain extent its inventor. By involving the architect in the development of machine systems, he sets a bidirectional process in motion: the adaptation of the design to the machine, and of the machine to the design. The multidisciplinarity of the discipline would be once again extended in the spirit of the masterbuilder’s paradigm by the example of Brunelleschi (Carpo, 2011). The architect would be the organizer of a conceptual strategy which covers the areas of design, material, structure and machine development. The forgotten relationship between the architect and the machine as an invented tool of fabrication would be revitalized. Like this the link between the design, the image of what is to be constructed, and the making of the materialization of this image is being reinforced.

3. Current State of Research

From the multitude of academic and non-academic robotic projects, three research endeavors conducted by Neri Oxman, Enrico Dini and Behrokh Khoshnevis, can be considered to play an exemplary role in the advancement of the field of self-developed robotic and machine strategies with regard to the implementation of 3D printing technology and to be important for the contextualization of the further presented case study.

Oxman engages in a holistic approach, developing a strategy which covers and intrinsically unites the processes of design and fabrication: variable property modeling (VPM) and variable property rapid prototyping (VPRP). Following the example of highly optimized natural material distribution, Oxman explains her methodology as an interlinked process chain of modeling, analysis and fabrication which results in objects which ‘correspond to multiple and continuously varied functional constraints’ (2011, pp. 16). At
the current state, VPRP is a technology which is not yet applicable for the construction site. One reason lies in the use of resins as construction material, while the second is connected to the size of the used machine, its reduced size depicting a considerable limitation to itself.

Developed by the inventor Enrico Dini, D-Shape represents a fabrication process which is very similar to general 3D-printing technologies following a horizontal layer-by-layer material depositing strategy. For this technology a custom-made material was developed, consisting of sand and a mineral binder, the result being similar to artificial sandstone (Jakupovic, 2013). Other than the resin and plastic composites used at other 3D-printing technologies, the custom-made material of D-Shape seems to implicate considerable benefits in terms of its sustainability, and material resistance. Contrary to VPRP, D-Shape proposes for now an undifferentiated material depositing system and can be considered a scaled-up version of an industrial 3D-printer.

Behrokh Khoshnevis, professor at the University of Southern California developed the technology of contour crafting (CC), defined as a method of layered manufacturing which may employ a diverse range of printing materials used for the realization of architectural structures (Khoshnevis et al, pp. 302). The technology distinguishes itself by taking various aspects of the construction site into account, which are neglected by most comparable projects. Besides offering a wide material range, from smart concrete to ceramics, it offers automated solutions for the integration of reinforcement elements, plumbing, electrical wiring and even tiling (Khoshnevis, 2004). Thus CC enlarges considerably the technological complexity of 3D printing in accordance to the intricate demands of architecture.

4. The Case Study

The previously described theoretical approaches and constructs will be exemplified and demonstrated on an applied case study. The case study at issue, bearing the name Minibuilders, was developed as a robotic research project at the Institute for Advanced Architecture of Catalonia in Barcelona.

4.1. PROJECT AGENDA

The main aim of the project consists in the development of a robotic fabrication strategy which is suitable for the on-site construction use and offers additional substantial benefits to existing technologies. Prior to starting to develop a precisely detailed project agenda, the first step of the research consisted in collecting data about the current utilization of robotics and the appendant employed materials. A multitude of diverse robotic technologies, most of which originating from car design, ship building and aircraft indus-
try, were investigated. Close attention was given to the academic field, as it offers a higher variety of experimental robotic applications. Another centre of interest concentrated on 3D printing technology and its architectural applications. As a second step, the collected data of multiple case studies was analyzed and evaluated, in due consideration of predefined comparative criteria. Subsequently the four following limitations of robotic arms were identified as main impediments in achieving a more complete implementation of robotics into the applied field of architecture:

- Limited reaching area.
- Limited mobility. In order to extend the reaching distance, robotic arms need to be moved on tracks or placed on moving platforms, which implies the input of additional effort and the creation of an infrastructure.
- Weight and size. The average weight of an industrial robot arm amounts to approx. 600 kg. This weight can represent an impediment in terms of fast and flexible motion, while on the construction site it depicts additional load which needs to be considered. The size of industrial robots corresponds to their weight, so that they can be considered as large-scale fabrication tool. A restricted accessibility can derive out of this.
- Restrained range of application. Excepting very few examples, such as the ICD/ITKE fibre-woven pavilion 2013/14, where the robot engages in a continuous construction workflow which results in a finished pavilion, robot arms are normally used to perform only parts of the fabrication, construction or assembly processes. Therefore, if we look at the entirety of building processes, they rather represent auxiliary, supporting tools assigned with secondary activities.

The identified disadvantages, enumerated in this list, represent features which can be interpreted as such from the builder’s standpoint, having in mind the construction site. In the context of their area of use, such as performing at an assembly line, these features represent high-value assets. Resulting from the before detailed analysis and the elaborated determining factors, the research group concluded on the following three objectives, as detailed below, to be covered by the developed project:

- The main set goal is defined as developing a robotic strategy which covers the construction process as a whole and is designed for on-site use.
- The second requirement aims at technical specifications regarding the aspect of scale. Other than industrial robot arms or building site equipment, the developed machines should exhibit the following features: lightweight, small size and autonomous mobility. Satisfying these demands leads to flexible, easy maneuverable machines. Yet, the reduced size and weight should impose no limitation to still being able to construct normal scaled structures.
Sustainability in relation to material usage represents the third set goal. Taking into account the general bias towards the non-standard curvilinear designs, the decision was taken to focus on offering a solution for fabrication challenges which derive from such geometries. Building curvilinear shapes often implies the use of an on-site scaffolding, an elaborate production of casting moulds or high figures of material offcuts. Thus material usage, energy footprints and labour time can be reduced, just by developing a technology which is not reliant on the use of scaffolding or moulds.

4.2. ROBOTIC CONSTRUCTION STRATEGY

Preliminary it is important to state that all focus and effort have been invested in the developing of an operational construction methodology. Therefore, this paper is concentrating on the attempt to highlight the relevance of self-developed robots and the importance of the interrelation between design-material-machine. Due to this approach, profound technical details concerning aspects of mechanical engineering or programming will not be described extensively. Following the same reasoning, the design depicted in the following pictures is irrelevant in terms of its formal aesthetics and was deliberately kept minimal. To meet the previously mentioned requirements a robotic strategy for on-site fabrication was developed.

The strategy is predicated on the development of a series of mobile robots, which can act independently from one another and thus fulfill separate functional demands. The three developed machines with their built-in technology represent a hybrid between robotics and 3D printing: while the mechanic specifications correspond 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 (Figure 1). Subsequently, after the foundation is finished, the second robot continues depositing the following layers and finalizes 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, equipped with a suitable climbing mechanism, continues with the successive deposition of the layers. As the deployed material is a fast hardening two-component resin system and the grip robot features two heating devices, which if activated, reduce the curing time, the extruded layers can accurately set on time and thus ensure structural stability and support for the grip robot to continue its movement. The grip robot is the robot which completes the form and is responsible for the main construction task.

![Image](image.png)

*Figure 2. From left to right: Grip robot finishing structure, vacuum robot moving vertically and depositing reinforcement layers, printed curved wall element.*

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 utilization of the vacuum robot. Whereas the foundation and grip robots follow a horizontal line of movement, the vacuum robot is designed for ensuring a vertical motion. As indicated by its name, the robot creates a vacuum between itself and the surface of the structure in order to be able to advance vertically (Figure 2). Similar to its predecessor, also this robot needs to be manually placed on the structure. It then moves along the structure, by following predefined paths. These pathways originate from a previous, detailed structural analysis of the design. They derive from force flow lines and represent abstractions of these lines, which were simplified
for printing purposes. After the completion of this last layer, both design and construction process can be considered as finalized.

4.7. MATERIAL SUPPLY AND DEPOSITING STRATEGY

All three robots are connected to an external, industrial extruder which contains two buckets filled with a custom-made, two-component resin system. The custom material was developed simultaneously and in accordance with the robots. In this case, robots and material are intrinsically connected to one another. Information on the material behaviour, which was gained from conducting a series of material experiments, operated as determining factor concerning the mechanical development of the robots. Material viscosity, mixing ratio and curing times would influence the extrusion rates and speed up to the physical elaboration of the robots. During the extrusion, the two-component system is being mixed together and then deposited as consecutive layers by the robots. Being a resin based system, after the mixing the chemical reactions induce the material curing. Depending on the layer thickness, outside weather conditions, temperature and humidity, and the adding of an external heat source, the curing time can vary or be influenced.

The applied robotic printing strategy and the operating mode of conventional 3D printing devices are similar in nature, but differ in so far as the way of the material depositing is concerned. A diverse range of different 3D printing processes exists, all of which are based on printing consecutive parallel cross-sections of the model. The grip robot discussed here follows a slightly different material depositing strategy. It deposits the layers as a continuous spiral and not as a sequence of parallel cross-section layers. This means that the finished design model is processed by a custom-made script which redefines the shape that is to be constructed as a continuous spiral.

5. Future Fields

A first step in the broader development of the showcased project would lie in the refinement of functional subdivisions according to the necessitated architectural elements. For now the foundation, walls and ceiling as one unit and structural reinforcement were addressed. Extending the list, for instance by adding windows, differentiating between exterior and interior elements, would lead to an increased number of specialized robots. One further advancement of the technology could lie in not only extending the types of robots but also the material range. For accomplishing this goal Variable-Property Rapid Prototyping could serve as an indicative paradigm (Oxman, 2010). This technology relies on the use of multiple materials, which can be variantly deposited, ideally influencing even individual material properties,
such as density, according to the specific structural or functional needs of the printed area. Another desirable and beneficial enhancement of the technology could lie in extending this additive manufacturing procedure by equipping the robots with the capability of simultaneously adding and subtracting material, so that small construction or material deposition errors can be rectified in real time. Autonomous architectural robotics is still in the early stages of development. In terms of architecture, judging by the number of academic ongoing research projects, this field depicts one of today’s main areas of research and focus. Efforts are being made to further implement these technologies in architecture and by this to catch up with other related industrial fields, such as transportation or industrial design, where robots represent an essential component and activity without them is unconceivable.

6. Conclusion

The described project with its underlying construction strategy depicts schematically both a work approach and a procedural method which are in an early beginning stage. Nevertheless, it illustrates the benefits of the involvement of the architect in the assembly of a comprehensive strategy which covers aspects of design, fabrication and machine construction. By engaging the architect into robotic development, he can implement and adjust fabrication or construction strategies which are fully adapted to architectural specific needs. Being involved in the mechanical development of the construction tools asks for a complete understanding and participation of the architect in the material research. By a detailed understanding of the material and through the collaboration with material scientists, it should be possible to generate modified materials according to the specific needs and demands of both the design and the machine, so that they best fulfil the requirements of the developed construction strategy. The machine turns into a design agent of equal importance with other parameters which influence the design and its materialized quality. Through the integration of self-developed machines or robotic devices as an autonomous design agent in the architectural process a complete liberalization and democratization of the discipline could be achieved (Anderson, 2013). The high level of skepticism regarding the dematerialization of architecture through the extensive use of digital fabrication tools proves itself to be superfluous. Gramazio and Kohler argue in benefit of the deep impact robotic arms had, claiming “that the robot engenders a fundamental alteration in the discipline’s constructive understanding of itself” (2014, p. 182). The robot is seen as a catalyst between architecture and construction, which strengthens further this relationship. If the potential of the digital is understood correctly and applied in a suitable way, the digital
can lead to the reinforcement of the material and constructive nature of architecture. Through the use of robots or robotic machines a convergence of architecture and a new type of handcraft is being facilitated.

The following quote by Kieran and Timberlake (2003) summarizes most adequately the potential which can derive from the simultaneous reengagement of the architect with different fields of specialization:

“While we cannot return to the idea of the masterbuilder embodied in a single person, the architect can force the integration of several spun-off disciplines or architecture - construction, product engineering and material science - all with the aim of reuniting substance with intent.”

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