Informed Design to Robotic Production Systems

Developing Robotic 3D Printing System for Informed Material Deposition

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This paper discusses the development of an informed Design-to-Robotic-Production (D2RP) system for additive manufacturing to achieve performative porosity in architecture at various scales. An extended series of experiments on materiality, fabrication and robotics were designed and carried out resulting in the production of a one-to-one scale prototype. In this context, design materiality has been approached from both digital and physical perspectives. At digital materiality level, a customized computational design framework is implemented for form finding of compression only structures combined with a material distribution optimization method. Moreover, the chained connection between parametric design model and robotic production setup has led to a systematic study of certain aspects of physicality that cannot be fully simulated in the digital medium, which then establish a feedback loop for underrating material behaviors and properties. As a result, the D2RP system proposes an alternative method of robotic material deposition to create an informed material architecture.

Keywords: Informed Design, Robotic 3D Printing, Porosity, Material-Architecture, Design to Production

INTRODUCTION

Informed Design-to-Robotic-Production (D2RP) systems explore the extents by which rapid and flexible robotic fabrication methods can inform and enhance generative design to materialization and production practices. In the case study of this paper, the focus is to experiment with the possibilities of an optimized material deposition system resulting from compression-only forces inside the computationally-derived topology. The study has explored the possibilities of designing and fabricating material architectures with various levels of porosities, ranging from architectural (macro) to material (micro) scales. By employing performative and generative computational design methods, industrial robotic production techniques and material experiments, the D2RP aims to close the loop from design to 1:1 scale fabrication. With this goal, the main research components of the presented case study are: materiality in relation to design computation and robotics in relation to 3D
The relation and integration of physical material properties within digital design interfaces and computer aided design methods have been explored and explained in both practice and academia (Borden and Meredith 2011) (Kolarevic and Klinger 2008) (Gramazio and Kohler 2008) (Oxman and Rosenberg 2007). In this context, we can specify two major types of approaches. In the first type, to study design materiality, the design system relies only on virtual modelling, simulation, analysis and abstraction of physicality through implementation of certain computation methods such as Finite Element Method (FEM), Computational Fluid Dynamics (CFD), Particle Systems, etc. The second approach focuses more on constraints and potentialities of certain material and/or a fabrication method integrated into digital modelling platforms, i.e a parametric design model. The proposed D2RP system establishes a feedback loop between the two. To achieve this goal, at digital materiality level, through designing and implementing of a systematic and chained strategy for design information exchange (Mostafavi et al. 2013) a customized parametric form finding system for compression-only structures combined with topology optimization is established and implemented. At physical level, the direct connection to the robotic production system, in addition to improving the production method has led to the direct study of certain aspects of physicality that cannot be fully modeled inside the digital design platform. Therefore, the production system becomes not only a means of fabrication but also simulation.

Recent research advances in both robotics and 3D printing fields have potentially introduced new approaches towards architectural materialization and production. Considering materiality and architecture at multiple scales, there are a few projects that successfully bring the two together. In some examples a scaled up printing machine that surrounds the envelope or object will be used to horizontally, layer by layer, deposit a certain building material (Khoshnevis et al 2006) (Kestelier 2012) (Dini et al 2013). The explored and presented robotic 3D printing project proposes an alternative method of material deposition to create a multi-dimensional material architecture. This is achieved considering the behaviours and properties of the implemented material, in this case ceramics, and integration of material optimization routines in the D2RP system.

**DESIGN AND PROTOTYPE**

Customizability of the production method, considering both research and design project objectives, has been taken into consideration in order to develop a unique D2RP system. In this section, we provide a short overview of the established design methodology through describing the pilot case study, robotic motion path generation in relation to the materiality and a description of the realized 1:1 prototype.

**Methodology and case study**

D2RP defines four main research components: design computation, tooling/production, robotics and materiality. Each set of experiments and design exercises explores possibilities of integration and establishing feedback loops between the four (figure 1). Parallel to the lab-based explorations for the development of the D2RP 3D Printing system, which are described in detail in the next section, a studio design project of the Hyperbody TU Delft group, conducted by the authors, was considered as a pilot case study.
(figure 2). In this project architectural and material porosity at various scales is considered as the main design driver and objective. Therefore the developed D2RP system is customized and implemented according to both particular research and design objectives of the project.

In order to develop a coherent computational design system, specific to this project the first step was implementing methods for form finding of compression-only structures, derived from the innate characteristics of the material. In addition to eliminating tension forces in the derived topology, this part of the design system was implemented as a parametric strategy to define the porosity at macro or architectural scale to fulfill certain functional and locational requirements. Furthermore, to achieve the micro porosity level, a finite element method for material distribution optimization was implemented on a part of the designed pavilion. This integrated optimisation routine considers local and global load and support conditions. To implement a generic and repeatable method on other parts of the compression only structure the challenge is to be able to parametrically change the method of finite-mode geometric representation like point cloud and mesh to the vector based or NURBs geometry. This was achieved by applying a segmental system in the very initial topology, retrievable at different stages of form finding and parametric geometric transformations (Mostafavi and Tanti 2014). By applying the computational design system, the designer is able to generate multiple configurations, in each distributing the compression only material where needed and as needed, considering the structural performance, at both macro and micro scales.

The challenge of the next step is to materialize these differentiated densities, creating unified topologies that express structural loads consistent to the design approach and robotic fabrication potentialities and constraints, paths and targets. At this stage various algorithmic form finding and optimization techniques, mostly in the Rhino-Grasshopper platform and Python scripting-language is developed and applied. This allows the systematic exploration and evaluation of design alternatives in the design-solution space, eventually providing the required information for production with the ABB-Robotstudio. Simultaneously, the initial material experiments and information sets informs the design process.

**Design Materiality and robotics**

Material optimization for robotic production informs the relevant ranges of robotic motion by implementation of parametric design control systems. This creates new standards for architectural fabrication and improves productivity and performance. For production purposes, the topology of the pavilion was subdivided into unique components. As the research progressed it became apparent that due to the sig-
ificant variety of custom building components featured in the design, the robot manufacturer’s software functionality needed further customization. For this purpose the D2RP team has implemented a link between the design and simulation environment (Rhinoceros platform and it add-ons) and the rapid code interpreter of Robotstudio. This part of the research led to a direct link between the design model and robot controller, thus enabling the implementation of a greater range of unique, longer, continuous tool paths (figure 3). Although it is important to note both the utilitarian and decorative qualities making ceramics such a widely used construction material, this paper will focus solely on its structural and emergent properties.

As construction material, clay-ceramics is commonly used inside compression-only structures. Traditionally, the structures based on compression perform through stability given by their significant mass. What the study aimed to prove was that by controlled material deposition, compression structures could become lighter, a significant improvement in their cost and thermal insulation performance. A way of achieving material deposition optimisation is controlling the parameters of the production setup. This is briefly described as follows.

The extruder system designed and built by D2RP manages a plunger-based mechanical extrusion of a diluted paste of ceramic-clay, water and additive pigments. Although numeric control of clay extrusion was experimented with and valuable results for dynamic extrusion were recorded while implementing a discontinuous porous pattern, due to shifting research objectives, for the fabricated prototype, solely continuous clay extrusion was used. A custom design routine was developed in order to extract and optimize continuous motion path based on the designed material architecture.

Throughout the process, extrusion speed was adjusted empirically according to observed structural and aesthetic considerations. Extrusion parameters were controlled through line-size and nozzle customization. These proved important factors to consider during initial experiments as well as during the fabrication routines. Nozzles of various profile-size and extrusion opening area were experimented with. For the fabricated prototype, a nozzle featuring a square, 1cm aperture was selected and used. Finally, within the study’s agenda of 1:1 fabrication and architectural performance aims, it can be concluded that the prototype achieves both improved 3D printing speed and reliability.

**Prototype**

According to the design brief, the architectural object connects to the surrounding urban environment in a series of pores varying in size according to structural and aesthetic design parameters. The fragment chosen for fabrication explores one of these connections materialising a piece of urban furniture at 1:1

![Figure 3](image-url)

Left to right: Chosen Fragment for 1:1 fabrication, informed point cloud on the chosen fragment, and one single generated continuous curve used as the robotic 3D printing path.
scale. As well as the integral structure, the prototypical piece is structurally a compression-only system. In this project, in addition to developing a customized design-to-production setup, the team achieved optimization in motion path generation. Common 3D printing techniques employ non-differentiated routines for slicing and ordering material layers into motion paths. The prototype was produced embedding fabrication potentialities and constraints into the design. Continuous material deposition was achieved through controlled extrusion guided by structural performance through robotic motion. It must be noted that, although the computational 3D model comes close to the actual prototype, the two entities remain different mainly due to emergent material properties. Differences between virtual and material exemplify emergent aesthetics inherent to the material behaviour of ceramic-clay. The emergent aesthetics inherent to the prototype is as much due to the 3D layering technique as it is due to how material extrusion varies along the path (figure 4).

Figure 4
Details: 3D model vs. emergent material architecture

The study into robotically-controlled material formation processes was inspired by the fast-pace at which the building industry develops, constantly finding itself in need of agile architectural solutions to design and fabrication processes. Prototyping plays a central part in this agile process. Prototyping involves design, realization and testing each result in real-life or laboratory conditions. By exposing ranges for feasibility in design, fabrication and exploitation, a rapid-prototyping approach becomes vital for avoiding failure, communicating successful results and foreseeing design opportunities and threats. In this context good integration between digital and material processes is vital; this is where this project redefines the potential of robotic building (figure 5).

D2RP DEVELOPMENT
In the context of contemporary technological customization with emphasis on the role designers and users have in the third and fourth industrial revolutions (Anderson 2012), the D2RP proposes a roadmap for development and improvement of robotic 3D printing technologies for fabrication of 1:1 building components. The roadmap is set in the context of an on-going physical-virtual feedback, tested in three initial studies, concluding with creating a direct link between design and production. Multi-coloured light robotic 3D printing, as the first preliminary study, involves mounting a colour changing light source on the robotic arm. This project addresses the characteristics of 6-axis-robot motion connecting them to properties and information extracted from architectural and structural digital design model. Being able to study the three dimensionality of robotic motion contributed to developing a new approach to 3D printing, different than slicing in layers printing techniques. This provided possible directions for defining a 3D printing method, in tune with the structural characteristics of the final prototype. The study of robotic motion defines the boundaries of the digital design-space in relation to the physical solution-space. Furthermore it informs the parametric setup with ranges of reach-ability and optimized orientations thus contributing to maximizing it. In addition, by numerically controlling the blinking pattern and light colours of the mounted source, by means of an Arduino Microcontroller, the team reached the goal of further extending design possibilities in such a way that multiple materials can be deposited at certain coordination based on the information extracted from the geometry in the CAD interface. As the first step, any given curve, in digital, is reproduced, in physical, with multi-coloured light curves captured by means...
Figure 5
Urban furniture, 1:1 scale prototype, compression only structure
of long exposure-time photography. Later this approach is tested on the whole designed pavilion represented by a network of curves (figure 6).

The robotic pattern project, as part of the second set of preliminary studies, focuses on drawing geometric patterns that explore variation in densities and resolutions to reach the desired porosity and functionally - in the case this paper structurally-graded material systems (Oxman et al. 2011). This informed the design of robotically controlled routines for material deposition. The established parametric system, derived from these experiments, involved: size of the overall shape, thickness of nozzle for material deposition, number of targets to describe robotic motion and method of approaching defined targets. As a consequence of these experiments the team formulated two categories of material deposition: continuous flow and on/off numerically controlled flow patterns. Both directions had specific benefits and limitations. Continuous material deposition involved a bigger abstraction of the drawing patterns, while compensating through a unified understanding of
Numerically controlled material deposition enabled a more accurate representation of the final prototype but the logic used for production was rather more fragmented (figure 7).

The ceramic robotic printing study explores possibilities of production of 3D printed building parts and establishes a production method where all parameters are calibrated for the developed physical set-up. The team designed an extruder connected to an end-effector mounted on the head of a robotic arm, where the material source was exterior to the robotic arm in order to maximize the freedom of movement and reach. In order to achieve an optimum multi-dimensional material-architecture and informed by previous studies on printing resolution and variation of material deposition, a customizable extruder-nozzle system was designed and tested (figure 8). Considering the fact that natural materials are not fully predictable different material properties like plasticity, viscosity, flow rate and short-term material behaviour at different robot-motion speeds, were in-
vestigated and documented in order to provide complete information sets for the next prototyping phase (figure 9 and 10).

CONCLUSION AND DISCUSSION
Advancements in robotic building can potentially foster the pace at which architectural design and fabrication processes co-evolve. It is possible to envisage a future in which building systems are customizable and increasingly automated. The D2RP developed by the TUD team is exploring and securing a future for informed porosity in additive material distributions. Porosity at macro, meso and micro scales, refers to the optimisation of spatial configurations and material distribution. It strives not only at controlling mass-void ratios but also at achieving an integral design, from overall building configurations to the architectured material itself.

The specific goal of the presented case study in this paper was to scale and regulate the concept and technology of 3d printing for architectural design and construction, by integrating it in an informed, chained design to production system. For the authors, it was important to develop the technology not as an isolated node but as an integrated working-operating module ready to be used and well connected to a real design problem. In a larger context, the additive D2RP project presented in this paper is part of Robotic Building (RB). This extended framework focuses on linking design to materialisation by integrating multiple functionalities (from functional requirements to structural strength, thermal insulation, and climate control) in the design (Bier, 2013 and 2014) of building components. The main consideration is that in architecture and building construction the factory of the future employs building materials and components that can be robotically processed and assembled. This requires development of multi-materials, -tools, and -robots D2RP processes, which will be implemented incrementally in the next phases of the project.

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