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Materially Informed Design to Robotic Production: A Robotic 3D Printing System for Informed Material Deposition

Sina Mostafavi and Henriette Bier

Abstract This paper presents and discusses the development of a materially informed Design-to-Robotic-Production (D2RP) process for additive manufacturing aiming to achieve performative porosity in architecture at various scales. An extended series of experiments on materiality employing robotic fabrication techniques were implemented in order to finally produce a prototype on one-to-one scale. In this context, design materiality has been approached from both digital and physical perspectives. At a digital materiality level, a customized computational design framework has been implemented for form finding of compression only structures combined with a material distribution optimization method. Moreover, the chained connection between the parametric design model and the robotic production setup has enabled a systematic study of specific aspects of physicality that cannot be fully simulated in the digital medium. This established a feedback loop not only for understanding material behaviours and properties but also for robotically depositing material in order to create an informed material architecture.

Keywords Informed design · Robotic 3D printing · Porosity · Material architecture · Material behavior

1 Introduction

Materially informed Design-to-Robotic-Production (D2RP) systems explore the extents to which rapid and flexible robotic fabrication methods can inform and enhance established generative design to materialization and production practices. In the case study of this paper, the focus is on experimentation with optimized

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S. Mostafavi (✉) · H. Bier
TU Delft, Hyperbody, Robotic Building, Delft, The Netherlands
e-mail: s.mostafavi@tudelft.nl

H. Bier
e-mail: H.H.Bier@tudelft.nl

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material deposition for a compression-only 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 design methods, industrial robotic production techniques and material science 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 deal with specific aspects of materiality in relation to design computation and robotic 3D printing. In this context, the chosen fragment of a computationally designed pavilion required translation of the optimization results from a finite geometry into a continuous robotic path for material deposition in order to create an applicable material architecture.

The integration of physical material properties into design by means of digital design interfaces and computational design methods has been explored in both practice and academia (Borden and Meredith 2011; Kolarevic and Klinger 2008; Gramazio and Kohler 2008). The historical survey with respective related cases and paradigms is not within the scope of this paper but relevant to the goals of the presented case. In order to position this project in this larger field of research two major types of approaches have been identified. One presents cases in which, in order 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 other one presents material experimentations and the design system focuses mostly on constraints and potentialities of certain material and/or fabrication method that is integrated into digital modelling platforms, i.e. parametric design models. The proposed D2RP system establishes a feedback loop between the two approaches. In order to achieve this goal, at digital materiality level, a systematic and chained strategy for design information exchange is established by designing and implementing a customized parametric form finding system for compression-only structures combined with topology optimization. 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 modelled inside the digital design platform. Therefore, the production system becomes not only a means of fabrication but also simulation.

Recent advances in both robotics and 3D printing have 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 is employed to horizontally deposit layer-by-layer building material (Khoshnevis 2004; Khoshnevis et al. 2006; Kestelier 2012; Dini et al. 2006). The explored and presented robotic 3D printing project proposes an alternative method of material deposition aiming to create a multi-dimensional material architecture (Fig. 1). This is achieved while taking the behaviors and properties of the implemented material into consideration, which in this case is ceramics, as well as by integrating material optimization routines in the D2RP system.

Fig. 1 3D model continues robotic single robotic path and emergent material architecture

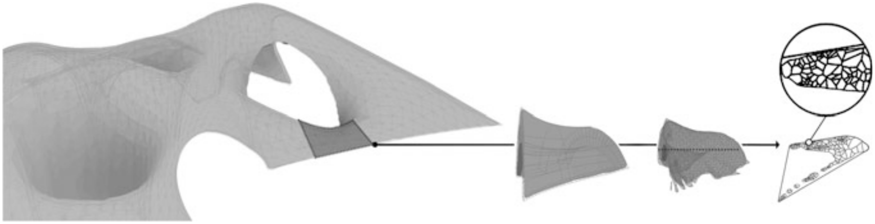


Fig. 2 D2RP explores multi-scalar porosity at building, component, and material level

D2RP consists of four main research components: Design computation, tooling/production set-up, robotics, and materiality. Each set of experiments and design exercises presented in the following section, explores possibilities of integration by establishing feedback loops between the four components. Parallel to the lab-based explorations for the development of the D2RP a studio design project was considered as a pilot case study. İn this project architectural and material porosity at various scales is considered as the main design driver (Fig. 2).

2 D2RP Development

The D2RP proposes a roadmap for development and improvement of a robotic 3D printing technology for fabricating 1:1 building components. The roadmap includes three initial case studies, concluding with creating a direct link between design and production: multi-colored light robotic 3D printing, robotic pattern studies, and ceramic robotic printing.

Multi-colored light robotic 3D printing involves mounting a color changing light source on the robotic arm. This project addresses the connection established between motion and information extracted from the virtual 3D model. Being able to study the three-dimensionality of robotic motion contributed to developing a new approach to 3D printing, different from the slicing-in-layers printing technique. 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. This informs the parametric setup with ranges of reachability and optimized orientations. It also contributes to being able to maximize the overall space used. In addition, by numerically controlling the on-off light pattern and light colors 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 virtual 3D geometry. As the first step, any given curve, in digital, is reproduced, in physical, with multi-colored light curves captured by means of long exposure-time photography. Later this approach is tested on the compression-only designed pavilion represented by a network of curves (Fig. 3).

As part of the second set of preliminary studies, the robotic pattern project focuses on drawing geometric patterns that explore variation in densities and resolutions to reach the desired porosity. This informed the design of robotically controlled routines for material deposition to reach a functionally graded structure (Oxman et al. 2011). 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 the robotic motion and the method of approaching defined targets. As a consequence the team formulated two categories of material deposition: Continuous flow and on/off numerically controlled flow patterns (Fig. 4).

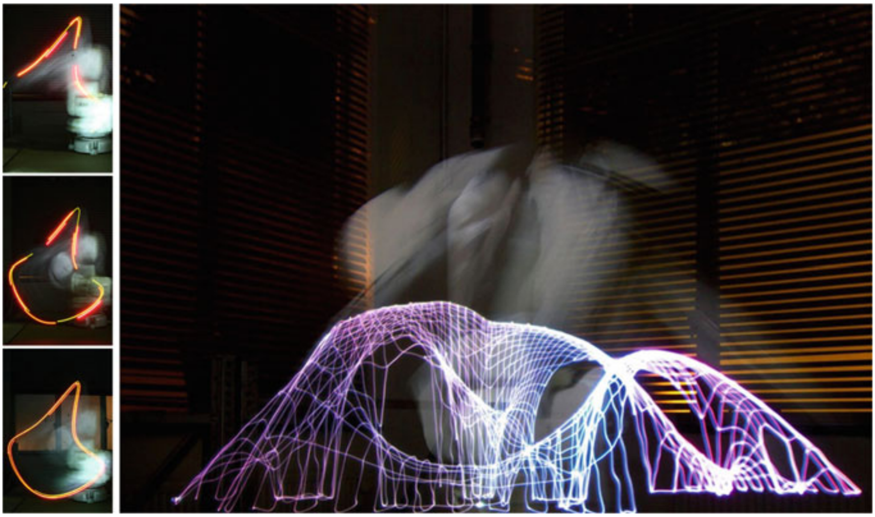


Fig. 3 Robotic motion: Multi-colored Light, 3D printing studies

Fig. 4 Pattern and material-architecture studies: on-off material architecture tests (*left*), differentiated porosity tests at material micro scale (*right*)

The ceramic robotic printing 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, in order to achieve an optimum multi-dimensional material-architecture. Initial experiments ranges from simple layer-by-layer material deposition to study material flow to 3D dimensional printing on doubly curved surfaces (Fig. 5).

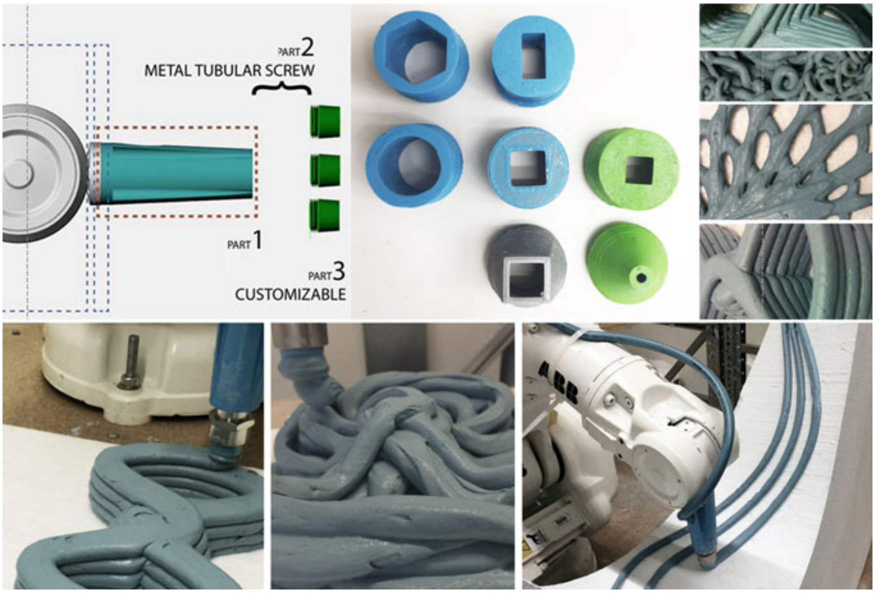


Fig. 5 Robotic 3D printing: Nozzle/resolution customization, tests on curved surfaces

Considering the fact that natural materials are not fully predictable several material properties like plasticity, viscosity, flow rate and short-term material behavior were investigated and documented at different robot-motion speeds in order to provide complete information sets for the next prototyping phase.

3 Design and Prototype

In order to develop a coherent computational design system specific to this project, the first step was to implement 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, in order to achieve the micro porosity level, a finite element method for material distribution optimization was implemented on a part of the designed pavilion. The optimization also considered local and global load and support conditions. To implement a generic and repeatable method on other parts of the topology, the challenge was to be able to parametrically change the method of finite-mode geometric representation like point cloud and mesh to a vector based or NURBs (non-uniform rational B-spline) geometry. This was achieved by applying a segmental system in the very initial topology, retrievable at different stages of form finding and parametric geometric transformation (Mostafavi et al. 2013; Mostafavi and Tanti 2014). By applying the computational design system several configurations were generated, in each distributing the compression only material where needed and as needed, while taking the structural performance at both macro and micro scales into consideration.

The challenge of the next step was to materialize these differentiated densities by creating unified topologies that express structural loads consistent to the design approach and robotic fabrication potentialities and constraints. At this stage, various algorithmic form finding and optimization techniques, mostly in the Rhino-Grasshopper platform and Python scripting-language, were applied. This allowed the systematic exploration and evaluation of design alternatives in the design-solution space, eventually providing the required information for production, path generation and kinematics simulation with the ABB-Robotstudio. Simultaneously, the initial material experiments and information sets informed the design process, design materiality and robotics. This was achieved through step-by-step documentation of a series of purposeful design-to-robotic production experiments with fixed and variable parameters. Specific to this project, the resulting dataset provides information on the possibilities of the developed D2RP system for robotic ceramic 3D printing, such as maximum angle of cantilevering, maximum length of bridging material without supports, minimum and maximum size of the nozzle, material flow, motion speed, etc.

For production purposes, the topology of the pavilion was sub-divided into unique components. As the research progressed it became apparent that due to the significant

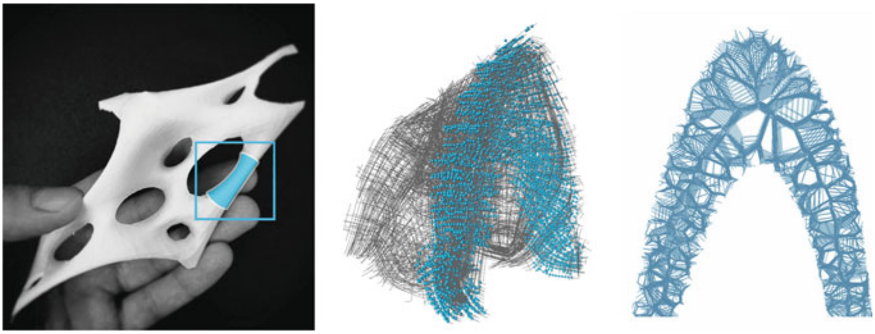


Fig. 6 *Left* to *right* fragment chosen for 1:1 fabrication, informed point cloud chosen fragment, continuous curve as toolpath

variety of custom building components featured in the design, the robot manufacturer's software functionality needed further customization. For this purpose a link between the design and the simulation environments (Rhinoceros platform and its add-ons) and the rapid code interpreter of Robotstudio has been implemented. This direct link between the design model and robot controller enabled the implementation of a greater range of unique, longer, continuous tool paths (Fig. 6).

As a construction material, clay-ceramics is commonly used for compression-only structures. The structures based on compression perform through stability due to significant mass and specific geometry. What the study aimed to prove was that by controlling the geometry and the material deposition, compression structures could become lighter, and significantly improve their material cost and their thermal insulation performance. A way of achieving material deposition optimization is by controlling the parameters of the production setup. This is briefly described as follows: The extruder system designed and built by the D2RP team manages a plunger-based mechanical extruder of a paste of ceramic-clay, water and a specific water based color-pigment that increases gluiness. The numeric control of clay extrusion was experimented and valuable results for dynamic extrusion were recorded, while implementing a discontinuous porous pattern. But due to shifting research objectives, only continuous clay extrusion was used for the fabricated prototype. Therefore, a custom design routine was developed in order to extract a continuous motion path to generate the designed material architecture.

To achieve continuous material deposition, similar to the challenge of translating mesh to NURBs in macro scale, in micro level a generic parametric system is developed to translate the discrete result of optimization to continuous curves (Fig. 7). In brief, the method involved picking a starting point and recursively searching in the extracted point cloud to generate a continuous spline. From topological and computational point of view, this helped the system to directly and efficiently provide an applicable tool path, considering material properties and behaviors and hardware-software specifications of the developed D2RP system.

Throughout the process the extrusion speed was adjusted empirically according to observed structural and aesthetic considerations. Extrusion parameters were

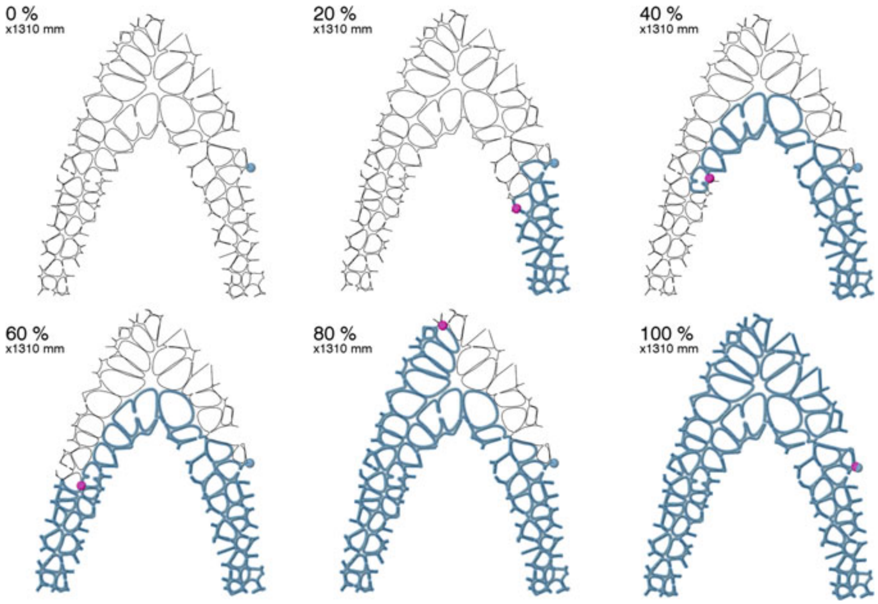


Fig. 7 Deposition process on one of the driven continuous curve from the discrete result

controlled through line-size and nozzle customization at the tip of the robot end-effector. We experimented with nozzles of various profile sizes and shapes. For the fabricated prototype, a nozzle featuring a square 1 cm^2 aperture was 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.

4 Prototype

According to the design brief, the architectural object was relating to the surrounding environment via pores of varying in size according to functional, and structural requirements. The fabricated fragment explores these connections, materializing a piece of structurally optimized compression only urban furniture at 1:1 scale. While developing a customised 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. 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. The emergent

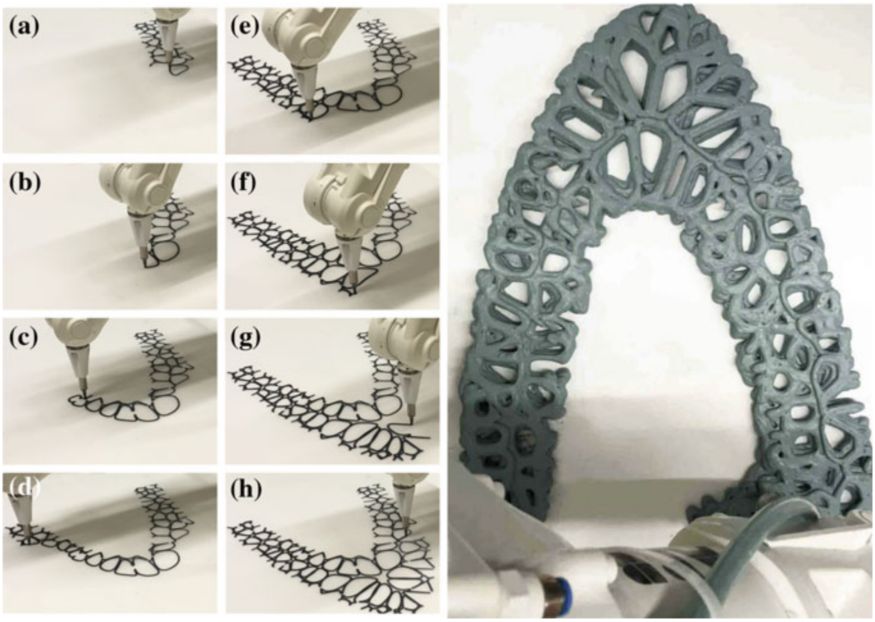


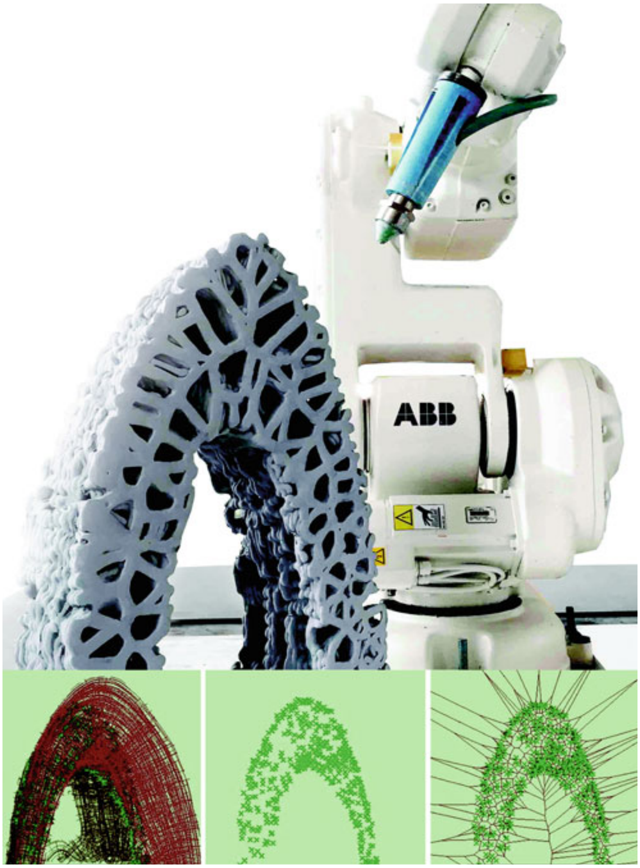
Fig. 8 Left: Test of the material deposition method (*left*), robotic 3D printing of the one-to-one prototype (*right*)

aesthetics inherent to the prototype are as much due to the 3D layering technique as to how material extrusion varies along the path (Fig. 8).

5 Conclusion and Discussion

Advancements in robotic building as presented in this paper indicate that future building systems are customizable and increasingly robotically produced and operated. The presented D2RP system demonstrates that informed porosity in additive manufacturing is relevant for the development of materially informed architecture. Porosity at macro (building), meso (skin), and micro (material) scales implies optimization of spatial configurations and material distribution. Using this approach we strive not only to control mass-void ratios but also to achieve an integrated design, from overall building configuration to the architectural material. In the context of the third and fourth industrial revolutions (Anderson 2012), the flexibility of such D2RP system can be understood with respect to the interaction between designers, users, and NC systems aiming to produce highly customizable and on-demand building components. Robotic Building (RB) eliminates the current problem of missed optimization opportunities due to a fragmented and sequential process of architecture—engineering—manufacturing. In a larger context, the additive D2RP approach presented in this paper is part of the Robotic Building (RB) project, which focuses on linking design to materialization by integrating multiple functionalities (from functional requirements to structural strength, thermal insulation, and climate control) in the design (Bier 2013, 2014) of building components.

Scaling up the technology of 3D printing from object to building was the specific goal of the presented case study. This was achieved by integrating the technology in an informed, chained design-to-production system, in which the 3D printing and robotics are not only ways of manufacturing but also methods and tools for simulation and testing of certain aspects of materiality, which lead to new opportunities for design exploration and creation. For the authors, it was important to develop the technology not as an isolated node but as an integrated working-operating module connected to a real-life design problem. The main consideration in architecture and building construction is that the factory of the future will employ building materials and components that can be robotically processed and assembled. This requires the development of multi-materials, -tools, and -robots for D2RP processes that will be implemented incrementally in the next phases of this research.



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