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Robotic Materialization of Architectural Hybridity

Modelling, Computation and Robotic Production of Multi-materiality

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Considering both architectural and constructional aspects of the built environment, hybridity or multi-materiality is essential to generate functional habitable spaces. Buildings consist of subsystems that each require different and sometimes conflicting material attributes and behaviours. In this context, expanding the solution space for material properties in architectural applications can be achieved through the integration of innovative design computation and production methods. With this focus, the paper presents prototyping processes and frames a discourse on robotic materialisation of architectural hybridity, ranging from micro or material to macro or component scales. The paper discusses three case studies, each with a specific focus on digital modelling, computation and robotic production of hybrid systems. The conclusion outlines how robotic fabrication of architectural multi-materiality redefines, informs and extends methods of design computation and materialisation.

Keywords: *Hybridity, Multimode robotic production, Robotic 3D Printing, Robotic subtractive manufacturing, Material computation, Multi-materiality*

INTRODUCTION

This paper provides an overview of design computation and robotic production of the building systems with multiple materials. It aims to identify and tackle some of the critical challenges in the materialisation of hybridity at architectural scales. In material science, the notion of hybrid material (Ashby 2011) refers to those engineered materials that may fill the holes in areas which are empty in the material property-space considering specific material attributes such as mechanical, thermal and optical. In

addition to these quantifiable parameters, the architectural design is concerned with functional, perceptual and aesthetic aspects of materiality. Therefore, the choice and production of hybridity go beyond mechanical properties. Moreover, advancements in digital manufacturing and robotics allow for the materialisation of architected materials (Brecht and Embury 2013). In architecture, this results in higher resolution and synthesis of different materials for building. From a theoretical point of view, this is changing the definition and role of ornament and de-

tail (Picon 2013) (Carpo 2017). Being able to work with wider ranges of materials makes the fusion of

natural and artificial possible (Brayer and Migayrou 2013) and facilitates a higher level of customisation



Figure 1
Hybrid of cork and expanded polystyrene, the prototype has a built-in hybrid behaviour that extends material properties of the two materials

of architectural spaces. This leads to what can be framed as user-driven, on-demand or opensource architecture (Ratti and Claudel 2015).

Figure 2
Detailed view of the robotically produced rigid cork boards milled with varied angles and depths



From an application point of view, these technological advancements for architectural materialization at multiple scales with multiple materials allows for the production of differentiation and performance-driven design solutions. These alternative production methods require integration of novel methods of material computation (Oxman and Rosenberg 2009). With a focus on multi materiality, the case studies of this paper explore, exemplify and discuss robotic materialization of architectural hybridity.

DESIGN TO ROBOTIC PRODUCTION PROCESSES AND PROTOTYPING HYBRIDITY

This research explores interrelations between different design scales, multiple fabrication methods and various building materials. Specifically, the presented work defines architectural robotics as a field of feedback and feedforward routines between computation, automation and materialization. The objective is to construct applicable building systems that are informed by quantifiable performance fac-

tors. The core subjects to be explained in each of the cases are computational design methods of multi-materiality, limitations of the various digital representation, modelling and simulation of hybrid materials, feedback loops through robotic production informing the design materialization processes and the process of developing customized robotic production strategies for architectural applications. Each of the presented prototypes is part or section of larger design projects with specific architectural objectives addressing structural, functional and environmental aspects.

Hybrid of flexible porous cork and hard polystyrene with varied thicknesses

The first one-to-one prototype is part of an indoor stage structure with sound absorptive capacities (Figure 1). The focus is on the integration of two different materials by using subtractive robotic production methods. The materials are cork and Expanded Polystyrene (EPS). Cork is placed in areas requiring either comfortable seating or sound absorption. The result is a hybrid building system with multiple incorporated functions.

During the first production stage, the thickness variation in the EPS components is decided considering structure and functions. Moreover, a sound reflection analysis informs the distribution of cavities between the two materials. Through the use of robotic milling from multiple sides, the geometrically complex EPS components become manufacturable. Further, specific patterns are three-dimensionally milled into plates of rigid cork to achieve flexibility (Figure 2) and to fit them onto allocated areas of the EPS components.

The most challenging aspect of this research is to estimate the three-dimensional bending behaviours of the yet two-dimensional shapes. This unrolling process is evaluated through a series of digital simulations and physical prototypes with a variation of milling patterns. While the first milling operation on EPS follows a common layer-by-layer approach of removing material, the second subtractive manu-

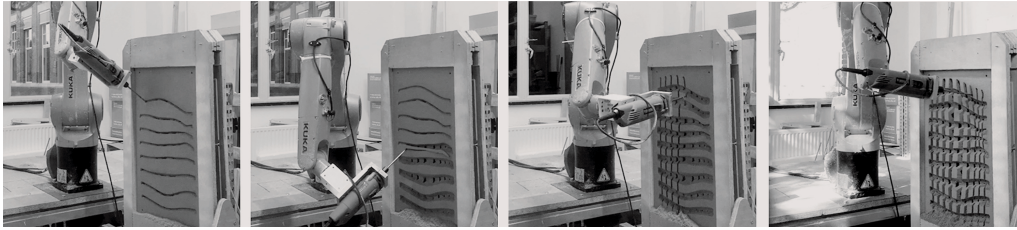


Figure 3
Multi-directional robotic milling of rigid boards of cork results in flexibility and bendability of the material to the target three dimensional geometry

Figure 4
Hybrid of concrete and intertwined permanent parts of the mould

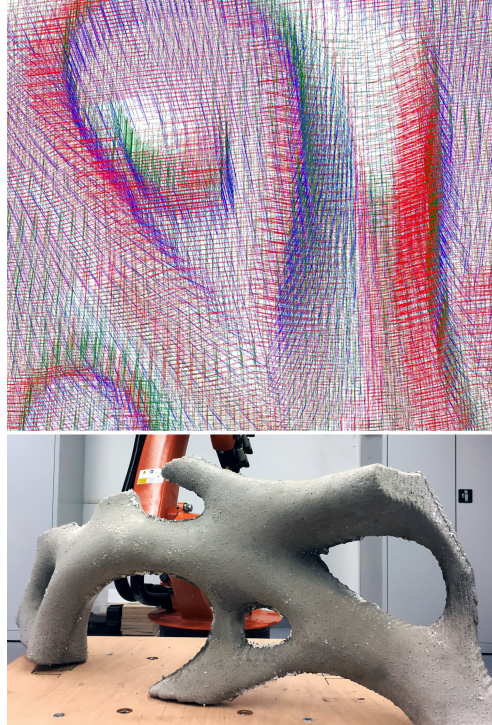
facturing method on the cork works differently (Figure 3). To achieve the intended bending behaviour, notches of material are removed from both sides of the rigid cork plates. This results in a multi-directional flexibility able to follow the targeted curvature. In a final step, the EPS components are connected to the two-dimensional cork plates, which are three-dimensionally bent and fixed onto the targeted areas. In this project, the incorporation of expanded polystyrene and cork boards into a building system, enhance individual physical properties. Even if both chosen materials share similar properties, such as rigidity, granulation and density, the robotic production system manipulates physical behaviours in favour of the expected design performances. In the case of cork, carving the planar rigid board from multiple sides, results in a double curvature element with flexibility, while being structurally supported by the polystyrene. The final prototype has a built-in hybrid behaviour that introduces controlled elasticity where the cork is not fully supported by the second material and stiffness in areas where the two perfectly overlap.

Hybrid of structural concrete and intertwined permanent parts of the mould

The second example is a hybrid system with concrete as structural and EPS as the second material (Figure 4). The EPS is acting both as a temporary casting mould as well as a permanent part intertwined with concrete that acts as insulation or finishing.



Figure 5
Top parametric tool
path for robotic
milling, bottom
prototype in
concrete only to
test predictable
ranges



The prototype is extracted from a building skin designed by incorporating structural and environmental analysis that results into an informed point-cloud. Based on this cloud, stress analysis and the properties of both concrete and EPS, the minimum to maximum dimensions are defined as well as variation in thickness. From a point of view of digital modelling of a hybrid system, this project presents challenges with respect to the translation of voxelised or discretised results of material computation based on topology optimisation into a continuous toolpath. To test the ranges of producible dimensions in concrete an initial prototype with a two-part mould is produced (Figure 5). In this prototype, the method of production and parametric robotic tool paths generated, with KUKA|prc in Rhinoceors® Grassopper 3D are generated and tested.

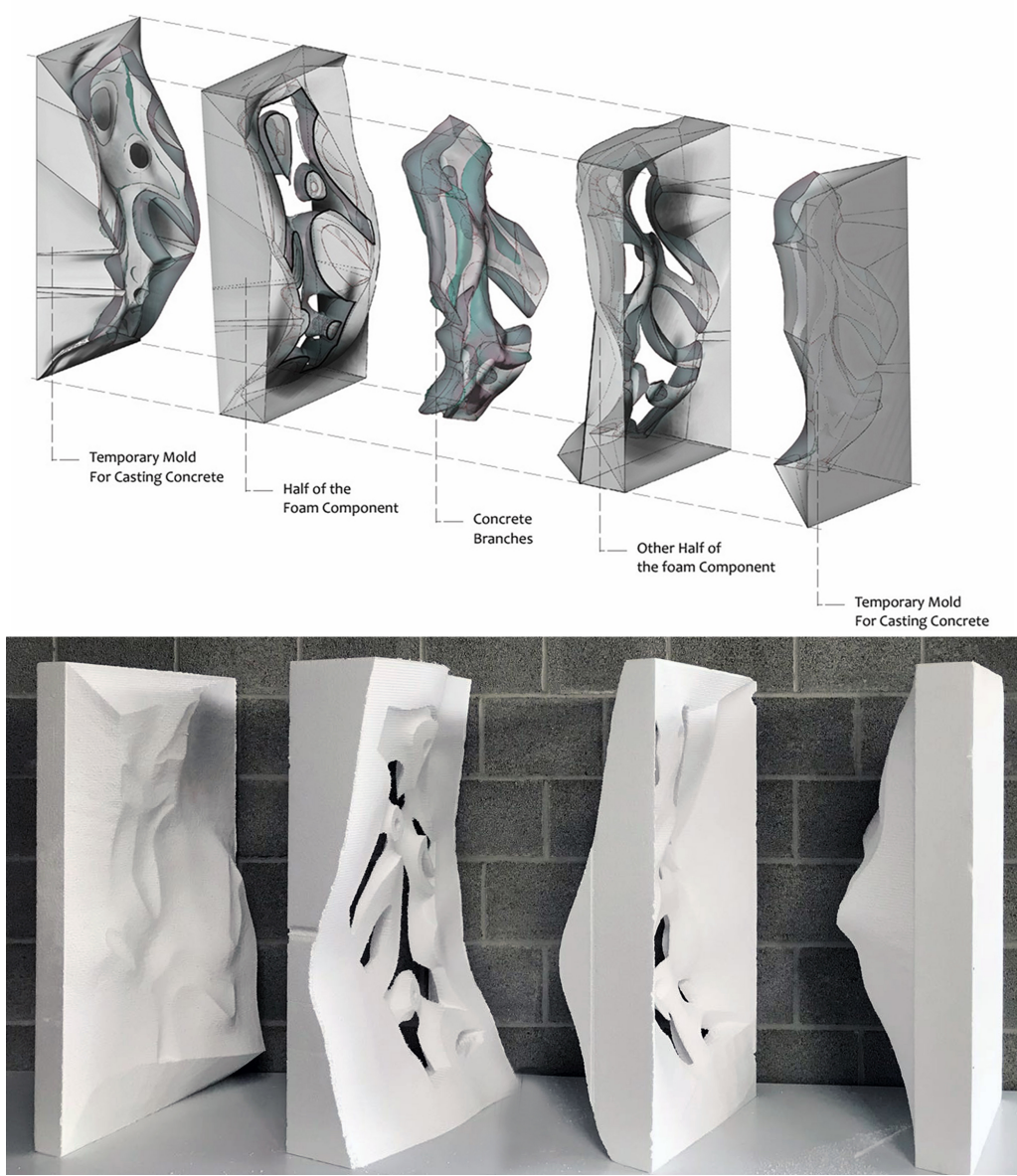
Unlike common two-sided moulds for casting, this cast consists out of four robotically produced components. Out of these four sub-components, two are closer to the concrete core and remain in place after stripping the formwork (Figure 6). This is due to the three-dimensionality of the concrete structure that interlocks two EPS sub-components together.

Hybrid of subtractively produced hard and additively deposited soft materials

The third case study focuses on the incorporation of subtractive and additive methods of robotic production. The design objective is to merge materials with different properties, such as softness and hardness together, to create a hybrid that allows for the integration of both external and internal functions (Figure 7). External functions may refer to embedding responsive cells in outer printed parts while internal functions may include flexible surfaces that are configurable according to local requirements such as soft seating. The project proposes a hybrid system composed of high-density EPS as hard and silicone as soft materials.

The research evolves along a series of experiments on silicone behaviour to understand the additive production of a semi-flexible material, as well as outcome properties and performance of the prototypes. Moreover, from the design perspective, the objective is to compute the distribution, density and morphology of the printed material for specific functions (Figure 8). This results in two main categories of cellular and linear silicone robotic toolpaths and ranges in between. A similar production method is previously implemented in a robotic 3D printing project on a freeform surface (Mostafavi and Bier 2016), while in this case the silicone as an adhesive material permanently stays in place. As the goal is to incorporate two production methods, sets of additive experiments are tested on freeform shapes. The results of these feedbacks are first, understanding the constraints and correlation between material capacities and second, the movement range of the arm and

Figure 6
Digital model and
robotically
produced concrete
casting mould with
two permanent and
two to-be-removed
parts.



printing angles with no support structure required.

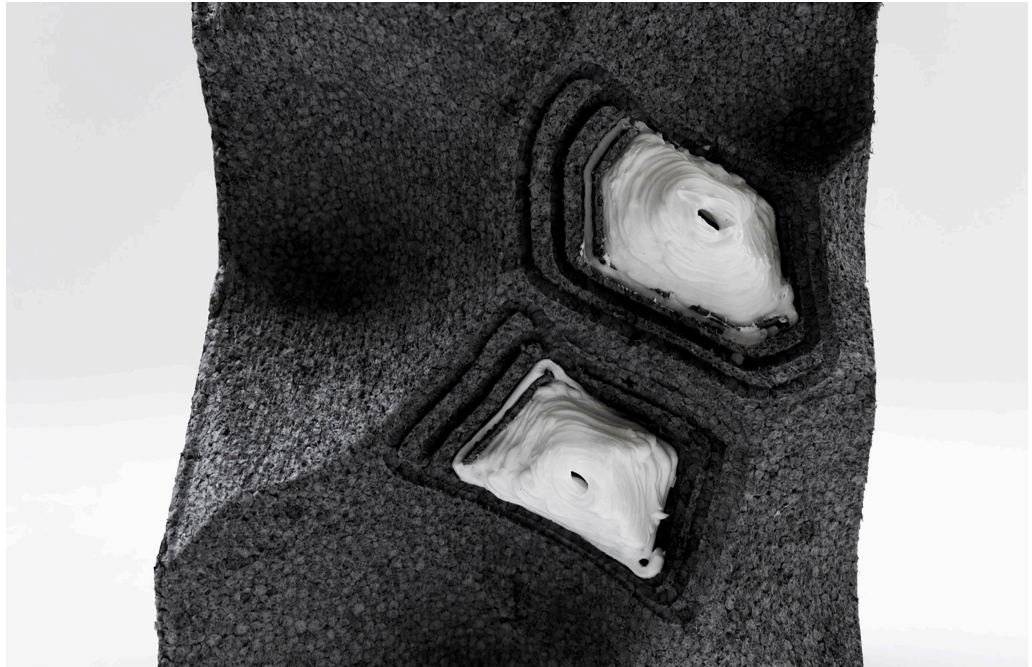
Exploiting the movement capacity of a six-axis arm, the extruder with two changeable material containers, i.e. transparent and opaque silicone is located on the axis three. Therefore the specific design of the extruder allows for a short connection to the nozzle, directly on the tip of axis six. This short connection on the one hand, enables higher ranges of three-dimensional movement of the nozzle on complex surfaces and on the other hand, a lower pressure is required to push or stop the extrusion. Since both subtractive and additive processes are executed with one setup, it is essential to inform the design through robotic simulation of both processes. As each of these processes has different optimum workable production space, it is important to know the overlap between these two optima. In other words, optimum positioning of the working object for robotic milling might be different than optimum positing for

robotic 3D-printing. To bridge the subtractive and additive processes initial 3D-scanning of the milled output and updates of the printing path is tested.

CONCLUSION

Robotic production of multi-materiality requires customized methods of digital modelling and design computation. Since most of the digital representation methods are not designed to model and compute hybridity, production feedbacks are essential to establish these new approaches. Through an integrated design to robotic production process, on the one hand, the constructability of design iterations can be evaluated, and On the other hand, the resulting producible hybridity introduces opportunities for efficient design materialization. As it is tested and elaborated in the case studies, in architectural design, the efficiency refers to the environmental, the structural and or the functional requirements.

Figure 7
Hybrid of
robotically milled
hard expanded
polystyrene and
additively
deposited soft
silicone



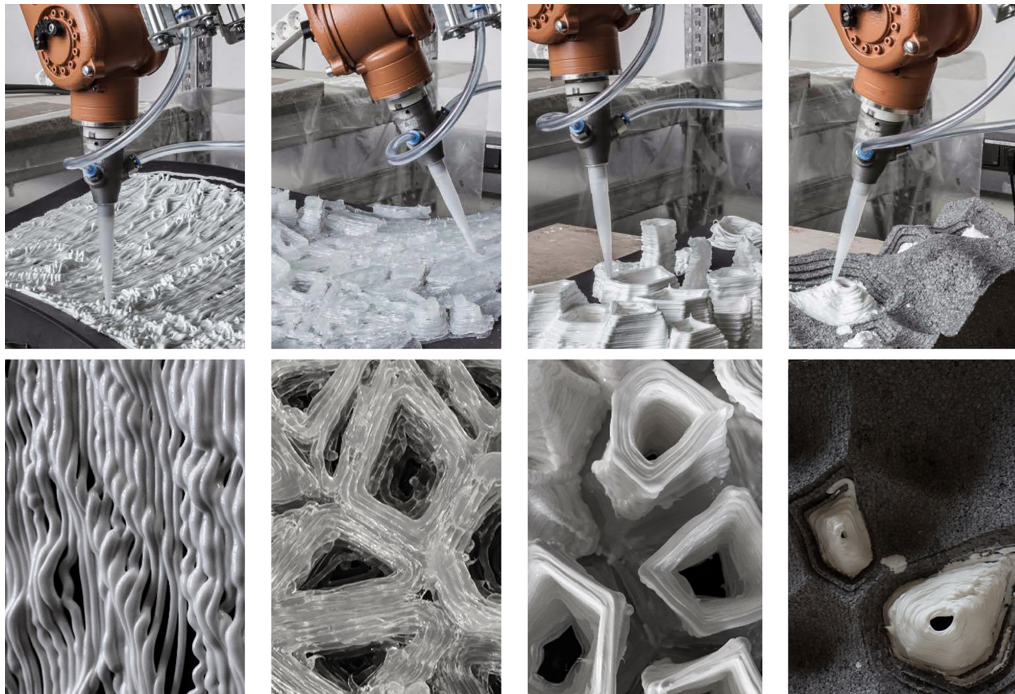


Figure 8
Series of test with
additive deposition
of soft silicone on
fabric and
robotically milled
hard components

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