FORM-FINDING WITH ROBOTICS

Fusing Physical Simulation and Digital Fabrication

TIAN XIA\textsuperscript{1}, JING LIN KOH\textsuperscript{2}, YUTONG CHEN\textsuperscript{3}, YI QIAN GOH\textsuperscript{4} and STYLIANOS DRITSAS\textsuperscript{5}

\textsuperscript{1,2,3,4}Singapore University of Technology and Design, Singapore
\textsuperscript{5}dritsas@sutd.edu.sg

\textsuperscript{1,2,3,4}\{xia_tian|jinglin_koh|yutong_chen|
yiqian_goh\}@mymail.sutd.edu.sg

Abstract. We present an experimental digital design and fabrication process investigating the integration of form-finding and industrial robotics. The design process is inspired by classical experiments producing minimal surfaces and tensile structures via physical simulation. The fabrication process resembles thermoforming whereby sheets of PET material are heat treated and while in a malleable state, where the material behaves like stretchable fabric, an industrial articulated robotic arm impresses a form while the sheet is air cooled and its final shape becomes stable and rigid. The three-dimensional plastic sheets are used as molds for glass-reinforced concrete casting. The key aspects of our approach include: (a) Mold-less fabrication: the design of our robotic end-effector can produce a range of free-form geometries without need for complex mold making (b) Reusable and durable artifacts: unlike traditional physical form-finding processes where the derived form is often ephemeral or fragile our process affords the detachment of a rigid artifacts which can be digitized, used as-is or employed in (c) Multi-stage fabrication: as the form-found geometry can be directly used for processes such as casting with excellent results in terms of surface finish. We present the design and development of our system and its deployment for an installation artwork.

Keywords. Form-Finding; Digital Fabrication; Architectural Robotics.

1. Introduction

Form-finding fuses geometry with aspects of its material characteristics such as tensile and compressive mechanical properties through design experiments historically involving scaled physical models, such as those by Frei Otto (Otto & Rasch...
The setup of such experiments often predetermines topology, high-level associations of physical entities, and predefines both the loading and boundary conditions. Materials and assemblies such as thin films, strings and chains, coupled with physical forces such as gravity or surface tension become the integrated modelling and simulation primitives producing beautiful artifacts often perceived as representations of larger scale architectural and engineering systems. The limitations of working with physical models such as soap films, hanging chains, and stretched fabrics, include time-consuming preparatory work in setting up the experiments, they are often difficult to reproduce, digitize and integrate within a broader design process and they are typically sensitive to damage or direct deployment for subsequent fabrication processes.

Computational simulations and parametric modelling enable faster cycles of experimentation using form-finding principles with representations which are certainly easier to integrate within the broader design process. Nevertheless, particle-spring systems, dynamic relaxation, finite elements analysis and computational fluid dynamics are relatively less intuitive than directly working with physical models. Due to the abstraction of physical behavior, they do not necessarily produce physically correct results; or they rather span a broader realm that what is exclusively physically plausible. In addition, the materialization of complex geometries generated through simulated form-finding within parametric Computer-Aided Design software requires advanced digital fabrication technologies which rarely can faithfully reproduce the combined material and geometry logic but merely the form.

Our work investigates the domain in between physical and digital design and fabrication. The objective of the presented work is to overcome the conceptual hiatus between physical and digital form-finding, address some of the aforementioned limitations of each approach and propose a new perspective which fuses materiality with its formation process. We arrived at this discovery through design experimentation with material formation processes using industrial robotics, see figure 1. In this paper, we present the design, development, testing and deployment of our process; a case study for the design of an artwork installation created through the process; and offer insights into the notion of robotically controlled form-finding.

2. Relevant Work

Digital design and fabrication had a profound impact on the architectural design thinking and making in both academia and practice. Indicative compilation of early work in the field is presented by (Kolarevic 2003; Iwamoto 2009; Dunn 2012; Glynn & Sheil 2012). Industrial robotics have been recently popularized as a general purpose digital to the physical medium for design experimentation (Brell-Cockan & Braumann 2012; McGee & Ponce de Leon 2014; Reinhardt et al. 2016). Of particular relevance to our work are experimental design processes that do not follow the orthogonal range between additive, such as 3D printing, welding or general assembly, and subtractive manufacturing such as Computer Numerical Control machining, turning and cutting. Research work relevant to digital design and
fabrication processes inspired by form-finding includes (Kudless 2011; Dierichs et al. 2012; Clifford et al. 2014; Prado et al. 2014; Culver et al. 2016; Bechert et al. 2016). The key features of our material and processes are closer to those used in the product design and manufacturing of consumable goods based on plastics, namely thermoforming (Kruysman & Proto 2012; Weissenbock 2014), blow molding and incremental sheet forming (Black & Kohser 2003; Bruninghaus et al. 2012; Kalo & Newsum 2014; Friedman et al. 2014) but also combine aspects of processes using molding and casting. As such the presented process is rather a hybrid multistage fabrication.

3. Process Overview

The presentation of the process is organized along the following sections: (a) Material Investigations: determination of thermoplastic materials for controllable and reproducible heat treatment which can be used for casting glass fiber reinforced concrete with high quality surface finish characteristics. (b) Design Tooling: design, development and testing of the robotic end-effector including electrical and mechanical integration of heat-treatment sub-systems as well as the material positioning apparatus. (c) Parametric Modelling: motion planning, robotics simulation and software with hardware coordination. (d) Deployment and Installation: digital design and fabrication of an artwork installation comprised of three hundred parametrically varied form-found components, see figure 2.
4. Material Investigation

Materials used for thermally controlled forming processes of thin wall plastic products such vacuum forming, stamping, blow and injection molding (Lefteri 2007; Howes & Laughlin 2012) are commonly thermoplastic polymers including High Impact Polystyrene (HIPS), Polymethyl Methacrylate (PMMA), Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), Polyvinyl Chloride (PVC), Polypropylene (PP), Polyethylene Terephthalate (PET) and High Density Polyethylene (HDPE). Thermoplastics exhibit a broad range of material properties such as mechanical, thermal, chemical, environmental and visual, which makes them suitable for specific applications.

The initial design direction included deploying the form-found thin shells directly into the artwork installation. As such beyond the behavior towards heat treatment, post-production durability and cost per sheet we also required high visual clarity. While most thermoplastics can be heat treated, they not all behave similar during. For instance, they melt at different rates which may be easy or difficult to control, and after the process is complete, for instance, they may become brittle or their opacity decrease, see figure 3. We evaluated PMMA, commonly known as acrylic, polycarbonate and amorphous PET (APET). We found the latter being the easiest to treat using a heat gun and quickly cool down using a blow drier, being able to significantly deep draw before reaching its breaking point, while retaining surface smoothness and without wrinkling, becoming brittle or foggy. Perhaps those are also exactly the reason it is the most common material used for water bottles.

The generated APET sheets were deployed for casting white cement reinforced with chopped glass fiber. The water to cement to glass mass ratios were experimentally determined at 15 : 25 : 1 against surface finish and strength characteristics. The presence of 2.4% glass fiber accentuated the glossy finish of the components which in combination with the texture free surface of the APET molds produced
results that resemble highly polished epoxied concrete. In addition, the glass fiber strengthened fine details and component edges which would have been extremely fragile otherwise, see figure 3.

Figure 3. Overview of molding and casting using glass reinforced white cement.

5. Design Tooling
The thermoforming system is comprised of the robotics end-effector, the material positioning apparatus and the electromechanical temperature control system. The initial concept regarding the end-effector was to design a quick change die system using 3D printed stamps. This is similar to conventional vacuum forming fabrication which requires molds upon which plastic sheets are formed. Experiments showed that the thermoplastic materials ABS and Nylon used for 3D printing were not suitable for dies as they deformed after a few applications even though they come into contact with the heated APET for only a few seconds. The next iteration of tool design was informed by the fabrication process of incremental sheet forming which uses blunt tool bits to progressively plastically deform thin sheet materials without removing stock or even heating. The benefit of this process is that it doesn’t require the shape of the end product to be transferred from a mold. It is thus less complicated in a number of sub-processes while enabling the fabrication of a wide range of geometries using the same tool. However, while it is more efficient than machining molds for thermoforming, it is also rather slow on per part production as it requires complex tool paths similar to CNC machining. The final end-effector was thus designed to mediate between multiple objectives, namely an increased volume of production, the simplicity of tool building and wide but not total range of geometric freedom. Using a simple blunt tool and by exploiting the multi-axis motion capabilities of the robotic system we were able of producing parametrically varied parts within the same family within seconds, see figure 4.
The interplay between the malleable plastic sheet and the rigid tool depressed against it produced artifacts not unlike the classical stretched fabric form-finding experiments by Otto. The unique aspect of the process was in the ability to rapidly set up physical experiments; fine tune the control parameters such as the elasticity of the material by heating, loading conditions by the robot motion and boundary condition by the tool shape; easily achieve reproducible the results; and most amazingly being able to obtain robust artifacts after the completion of each experiment. Discovery of those characteristics reoriented our thinking towards experimenting with digitally controlled, robotically fabricated form-finding investigating those artifacts that could perhaps only be generated through our process. We abandoned the notion of producing a conformed shape through a mold or progressively reaching a target surface and let the physics of the material and robot induce it.

6. Parametric Modeling
Integration of the electromechanical components of the digital fabrication system was implemented using Rhinoceros Grasshopper as the parametric modelling platform; Jenятияff digital design and fabrication library and Python programming language for motion planning, simulation and code generation; and Firefly and Arduino microcontroller for communications and signal processing, see figure 5. The sequence of tasks includes: (1) Loading a sheet of material into the positioning jig. This is performed manually upon which the digital process is triggered. (2) The material is heated on high heat for 20 seconds until it becomes malleable. The Arduino receives a timed signal from the laptop to turn on the heat gun and initiates an internal timer upon which it triggers the robot motion. (3) The robot approaches the positioning jig rapidly, pauses for a few milliseconds to reduce vibration and then begins descending slowly imprinting the material. (4) The heat gun is turned off and the blow dryer is turned on to rapidly cool the plastic. After a few seconds where the material has solidified, the robot motion is triggered again. (5) The arm is removed by playing backwards the same motion and the process can be repeated from step one.

The system architecture is comprised of multiple sub-systems which while individually they perform simple tasks, complexity emerges from their interfaces. The control logic is unidirectional as there were no sensors integrated into the system. Instead, the process is controlled by careful timing upon motions and signals.
are coordinated, see figure 6. Design parameters were derived from experiments. The data collected established boundary conditions such as the minimum and maximum amount of time required for heating before initiating forming as well as before causing changes in opacity, the maximum draw depth and twist angle before the material becomes too thin for casting, and the amount of time required for cooling before retracting the tool.

7. Deployment and Installation

The process was deployed for the creation of an installation artwork located on the campus, see figure 7. The design case study offers the opportunity to examine the efficiency and scalability of the process, identify its bottlenecks and limitations as well as fine tune our system towards context specific aesthetic objectives and technical requirements. It is comprised of 280 components arranged in a hexagonal grid. The design pattern was computationally generated using parametric design principles by data mapping. All components use the same tool die but the parameter of draw depth is individually varied based on a global gesture. The variation of profile depth is imperceptible except from certain viewing orientations where the
natural light reveals the overall glyph from the shadows cast. The rotation angle is fixed among all elements to 45 degrees. We found that excessive variation of multiple parameters produced rather verbose outcomes. Instead, we determined a constant angle that produces artifacts upon cursory observation appear simple and consistent; yet upon closer examination, it is evident that they could not have been produced by conventional fabrication procedures as the creases and folds of the cement hint of the impossibility of demolding such forms, see figure 8.

Figure 7. Photograph of overall installation. Photography by Frank Pinckers.

Hexagonal tiles are inscribed in 160mm diameter circle and measure 100mm along the flats with depth from 30mm to 80mm. They weight approximately from 0.5Kg to 1.5Kg which towards the upper range become problematic for support against a flat wall using conventional construction mortars and grouts. We experimented with weight reduction by creating double-sided molds using a pseudo offset APET surfaces produced using the same process and infilling the two plastic layers to create very fine thin shells. The glass reinforcement produced indeed
very lightweight and strong parts. We investigated embedding fasteners and introducing textured patterns on the back side of the castings for mechanical support but this approach also increased the complexity and hence abandoned in favor of directly mounting the tiles on the wall. We experimented high performance adhesives based on polyurethane, epoxy or compositions thereof and after load testing of up to 80Kg in shear, we concluded with a high strength construction adhesive product.

8. Conclusions

Digital design and fabrication technologies such as parametric modeling and industrial robotics through the integration of software and hardware offer opportunities for creative experimentation with material transformation processes in ways which could not have been achieved in the past. Of particular interest to us is the realm of processes that no longer either attempt to map traditional human actions of design thinking and construction into the digital medium or the enforcement of design thought into materiality by powerful machinery such as the design complex forms machined or 3D printed in absence of material integration. Certainly, those are valuable in automation of construction, manufacturing and general engineering but there are opportunities to discover new processes some of which may become the new norm. The concept of deriving artifacts, sometimes driven by aesthetics, sometimes by functional requirements, preferably by combinations thereof, from the interplay of materiality and the formation process is what is inspiring in form-finding. The presented process and case study offer a general approach to thinking and making at the boundaries between physical and digital design.

Acknowledgements

The authors would like to express gratitude to the SUTD-MIT International Design Centre and the SUTD Digital Manufacturing and Design Centre for supporting the research work.

References


