Robotic Design-Fabrication

Exploring Robotic Fabrication as a Dynamic Design Process

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This research explores the relationship between digital design and digital fabrication, investigating robotic fabrication as a dynamic design process. It examines the potential of utilizing production tools as the key part of the design process, where the final geometry is neither simulated nor pre-defined in the digital realm before materialization. This "design-fabrication" or "design-by-fabrication" workflow fosters a new way of thinking about architectural design and practice, as well as unlocking creativity and discovering new geometries and aesthetics. To illustrate this, the paper presents a series of directed design experiments developed by students in two seminars at Graz University of Technology. A unique fabrication technique is investigated, combining laser cutting and robotic thermoforming, which was developed by the author in the course of her PhD-research. Utilizing this robotically aided design process, sheets of acrylic glass are laser cut and thermoformed by a robot into 3-dimensional spatial objects, each element with individual geometries, textures, transparencies and apertures.

Keywords: Digital fabrication, Robotic fabrication, Laser cutting, Thermoforming, Material manipulation

INTRODUCTION

Due to the development of new software interfaces, programmable machines are more easily accessible to architects and designers. Custom plug-ins like KUKA|prc [1] or HAL [2] for Grasshopper allow architects with little or no scripting background to program machines like industrial robots. Within seconds, digital parametric set-ups and, therefore, robot codes can be changed. Processes are rapidly accelerating, and design as well as materialization of architecture can be individualized and customized with little time and effort. This development in digital fabrication significantly changes the relationship between architects and digitally driven machines, and opens up a new perspective on the connection between digital and physical. Architects gain more control over materiality and are able to extend the digital design process into the production process. The role of the architect changes, and an experimental approach to materializing architecture is facilitated.
This fosters a new way of thinking about architectural design, its workflow, practice and aesthetics.

This research aims to use industrial robots for architectural design in a creative and effective way, utilizing their full potential to enrich, inspire and transform architectural design processes. It suggests an alternative use of digital fabrication tools as design tools, complementing the design process on the computer with robotic technology. The goal is to not only integrate digital production in the design process, but to use it as an integral part of the design process, where the final geometry is not simulated or pre-determined in the digital realm before materialization. This paper investigates architectural workflows as process-based, flexible and not pre-defined, exploring "robotic design-fabrication" as key to a dynamic design process.

Furthermore, the paper describes a novel design-fabrication process, combining robotic thermoforming with laser cutting, developed in the frame of the author's PhD thesis (Weissenböck, 2014). The paper reports on recent case studies experimenting with this process that are created at the intersection of research and teaching at Graz University of Technology. In two "digital fabrication" seminars devised by the author, participating students develop several customized prototypes with individual shaped surfaces, textures, transparencies and apertures (Figure 1). Sheets of acrylic glass are laser cut, slotted or perforated, and shaped into 3-dimensional objects using robotic thermoforming. Using a digital parametric set-up, variations in the process can be made within seconds, enabling the creation of a myriad of forms and qualities. For production, a 6-axis industrial robotic arm - an ABB IRB 140 - and an Epilog laser cutter, combined with hot and cold air, are used.

DIGITAL DESIGN - DIGITAL FABRICATION
Nowadays, machines have interfaces that are more easily accessible to architects and designers, which allows us to gain a different view of digital-physical relations. As Menges describes it, "A novel convergence of computation and materialisation is about to emerge, bringing the virtual process of design and the physical realisation of architecture much closer together, more so than ever before" (2012). Current investigations in digital architecture aim for an integration of fabrication issues in the design process, especially benefitting from the exploration of material qualities and enabling an interplay between the digital and physical realm. "Digital and material orders enter into a dialogue, in the course of which each is enriched by the other" (Gramazio and Kohler, 2008).

In architectural design processes, materiality and physical models have always played a crucial role. Traditionally, hand-made models are used as design models or sketch models on the one hand, and as clean presentation models for clients on the other hand. In the beginnings of digital modeling, CAD software was merely used for precision and representation issues. In the late 1990s, the use of digital tools transitioned crucially. 3d-modelling or animation software is used for design, instead of representation. In his book "Animate Form", Greg Lynn writes about the changing role of the computer as form-generating tool, using a dynamic process for form finding (1999).

As before in digital design, in digital fabrication the mode shifts too, from using it as a representation or materialization tool of pre-given designs, to using it as design tool, implementing material qualities. Gramazio and Kohler define the term "digital materiality" in 2008: "Digital materiality evolves through the interplay between digital and material processes in design and construction" (2008).

Investigating this field further, this study aims to find new synergies between hand crafting, digital design processes, fabrication processes, and materiality. Largely, prototyping and digital fabrication are used to check the physical result of a finished digital design and to materialize complex digital designs respectively. In these explorations, digital fabrication is not investigated as a production process for already designed geometries, but as a "design by production" process, and "design-fabrication" is not defined
as a technique to fabricate complex designs, but to "create" complex designs.

ROBOTIC DESIGN-FABRICATION

Currently, architects and designers are passionately exploring the application of industrial robots in architecture. It was pioneered by Gramazio and Kohler in 2006 at the ETH, investigating the robotic assembly of bricks, and by Epps of Robofold in 2008, exploring robotic folding of metal panels. In 2010, Brell-Cockcan and Braumann founded the Association of Robots in Architecture, with the goal to "make industrial robots accessible to the creative industry". In 2012, they organized the first RoboArch-conference, on robotic fabrication in art, architecture and design, investigating the field of "...re-using industrial robots as a well-established basis and adapting them for architectural purposes by developing custom software..."
Compared to other digital fabrication machines, the use of robotic fabrication in the architectural design process offers some main advantages and potentials. One of the main benefits of robots is their possible application for a huge variety of tasks, offering the option to work with custom end-effectors. "... it has not been optimized for one single task but is suitable for a wide spectrum of applications. Rather than being forced to operate within the predefined parameters of a specialized machine, we are able to design the actual 'manual skills' of the generic robot ourselves" (Gramazio & Kohler, 2008).

The robot is also very flexible in terms of size and scale. In contrast to a robot's spatial flexibility, other fabrication machines like 3d-printers or milling machines have pre-defined maximum work volumes, which precisely limit the maximum dimensions of a thereby fabricated piece. A robot can provide a much larger field of operation, as it can move around or along the fabrication object.

Robotic fabrication is not just another way of digital fabrication, but has the potential to change processes in architectural design and build practice into a dynamic design-to-build-process. "Designers have taken the flexible nature of industrial robotic technology as more than just an enabler of computationally derived formal complexity; instead they have leveraged it as an opportunity to reconsider the entire design-to-production chain." (McGee, Ponce de Leon, 2014)

**A NEW DESIGN-FABRICATION PROCESS: EXTENDED ROBOTIC THERMOFORMING**

Recently, the potential of thermoforming utilizing robotic technology has been explored, i.e. at University of Innsbruck's RexLab [3], as well as by the Association of Robots in Architecture [4], creating free-formed surfaces by forming acrylic glass panels. In the research initiative "IsoPrototyping", Fereos and Tsiliakos investigate thermoforming using a transformable dry mold, "capable of manufacturing any given double curved surface" (2014). Thermoforming has a huge potential for implementing digital materiality, benefitting from special properties of materials that become malleable when exposed to high temperature. They allow for process-based deformations to create 3-dimensional shapes from flat surfaces.

As mentioned before, this study explores a new design-fabrication workflow, extending robotic thermoforming processes by combining them with laser cutting, and creating prototypes by forming flat acrylic glass panels into individual shaped objects (Weissenböck, 2014). In this chapter, the key-points of this workflow are described.

**Combining laser cutting and robotic thermoforming**

Cut-and-form processes have been widely explored using handcrafting techniques. In her publication "Soft Shells: Porous and Deployable Architectural Screens", Sophia Vyzoviti illustrates form generating experiments, using a "cut-stretch" process to thermoform pre-cut elements, stretching them by hand (2011). Another variation explored by Heimo Schimek involves a cut-and-form process using heat and gravity for shaping - a slotted plane is put onto a rigid mold and heated in an oven, where a bowl is formed by letting the material fall into its final shape by gravity [5].

In this study, a new technique is developed by combining cut-and-form processes with industrial robots. By means of this combination, it is possible to achieve customized elements of different shapes and variable apertures, as well as transparencies and surface treatments. Furthermore, this process uses the advantages of robotics over handcraft, implementing efficiency, precision, strength, scalability and reproducibility - yet still engaging materiality.

The application of cuts and scores to a surface influences the way it deforms. If more cuts or perforations are applied, possible deformations get bigger, because the material malleability increases. In addition, the size, depth and position of laser patterns influence the resulting geometry, i.e. special
cuts or scores can be applied to create intentional kinks, edges or breaks on certain positions.

Design and fabrication processes are programmed parametrically using the full potential of digital technology. Rhinoceros 3D software is used together with Grasshopper, its integrated graphical algorithm editor. The robotic procedures and the RAPID code are programmed with HAL [2], a Grasshopper plug-in for industrial robots programming. Therefore, each panel can be deformed at any number and positions of target points. Depending on the point, depth and angle of deformation in relation to the laser-cut pattern, different geometries and apertures of different sizes and shapes are created.

The laser-cut operations are applied to the material before thermoforming. Different operations are applied to the acrylic glass panels, to produce individual elements with different qualities. To create different textures, scoring is applied by the laser cutter. Scoring, rasterizing and perforating is used to achieve different transparencies. Perforations and/or cuts are applied to create apertures. The most challenging operation to create openings is the "cut+form"-technique, where the apertures are only produced during the robotic forming process by opening up the pre-cut slots of the flat surface (Figure 2).

**Robotic forming as a dynamic mold**

The question of fabricating complex curved geometries without utilizing single-use molds still prevails in architecture. In this study, a special kind of "dynamic mold" is developed to form flat sheets which are heated and robotically pushed against a form-giving counterpart: the "deformer tool". This means that the robot’s movement together with a deformer tool acts as a dynamic mold, capable of implementing complex movements like push, twist and tilt. The produced geometrical outcome is defined by the robot’s path in conjunction with the shape of the deforming counterpart, which is overlaid with the laser cut pattern and the material properties.

After laser cutting, the panels are placed into a custom-made frame that is attached to the robot’s flange. The panels are robotically shaped by moving them along a pre-defined path with different stations. First they are placed above the heat gun, then they are formed by pushing them against a deformer-
tool, and finally they are cooled down by a cold air fan (Figure 3). Variable shapes and sizes of deformers can be used to create panels with different geometries.

To create a wide spectrum of different shapes, custom-made deformer tools are developed that shape the surfaces by pushing them. In addition to spheres and sticks, geometries like semi-spheres, pyramids, cones or cuboids, as well as combined shapes like a 3-pin are used. In coordination with the laser pattern and the robot movement, individual deformer tools are designed to form unique prototypes.

**Designing processes**

In this study, design to production workflows are investigated as process-oriented. We design processes rather than shapes or forms. The goal is not to use robotic fabrication to materialize a geometry, which has already been designed on the computer, but to use robotic fabrication to design geometries. Since the robot is such a flexible tool, the predefinition of the fabricated geometry is not necessary and - in this study - not desirable prior to production. A different relationship between man and machine is established where the machine evolves from a tool to a partner (Hirschberg, 2014).

In the experimental case studies described in the next chapter, the final shape of the prototypes is not defined on the computer - rather digital processes are designed that are directly executed by the robot. These processes are designed based on material experimentation, architectural knowledge and intuition. The final design emerges during production - the execution of the code - especially taking account of material properties. The result is anticipated or even expected, but not always fulfilled. Surprises, discoveries and accidents happen, building up
a foundation for iterative optimization, as well as fostering creativity. As mentioned before, parametric tools enable adjustments in the process within seconds, enabling the creation of a myriad of forms and qualities, responding to different conditions. Variations of prototypes are created and optimized, exploring multiple solutions within minimal time and effort, which are precise, scalable, and repeatable.

EXPERIMENTAL CASE STUDIES
This chapter reports on selected students' work that was the outcome of two "digital fabrication" seminars, recently taught by the author at Graz University of technology. In these seminars, robotic fabrication is explored as an experimental design tool. The robotic design-fabrication process described in the previous chapter, is used to create individual case studies of modular elements. Prototypes are made from square sheets of acrylic glass in different transparencies, in a module size of 30 by 30 cm, and 3mm thickness.

In the seminars, the students combine manual production with digital production (Figure 4). In the first session, hand-deforming of panels is explored to introduce the participants to the material behavior of acrylic glass when exposed to different temperatures. By hand-testing, the students investigate possible shapes and design outcomes. These manual experiments are crucial to building up a design intuition and design intent that informs the digital process. As Bechthold and King describe it, "...physical and digital experiments produce many ideas in rapid sequence. Rough prototypes, even those produced manually, provide early feedback on opportunities, but also help failures to emerge quickly. The evaluation criteria derived through the analysis are used to filter out ideas for further development..." (2014). After producing first test models manually and digitally, students are able to select the most successful experiments and continue in a more focused way. In this seminar, each participant has to define the desired qualities of their project, the laser-cut pattern, the robot path and the deformer tool. After exploring test panels by means of manual and robotic forming, students have to develop four final prototypes in variation of a module.

Prior to the seminar start, a parametric code definition is set-up in the software combination of Rhinoceros, Grasshopper and HAL (Figure 5). This enables students without a programming background to program the robot easily, and adjust processes simply by moving sliders. The students appreciated the advantages of digital and robotic technology to fine-tune processes parametrically and to precisely repeat successful prototypes. Prior to robotic production, the simulation of the robot path is simulated in HAL and double-checked in ABB RobotStudio. The used fabrication machines are an Epilog laser cutter and an ABB IRB 140 robotic arm, combined with multiple heat guns.

The main constraints in this seminar are defined by the range and payload of the available robot, as well as by the limited availability of time and material. Besides materiality, the main influence fac-
Factors in this design-fabrication process are the laser-cut pattern, the geometry of the deformer tool and the robot path performing movement operations like push, tilt or twist. Further important parameters are the heating time of the panel, the robot speed during deformation and the cooling time at the maximal deformation point, to keep the deformed shape of the prototype.

Case study 1: Slices
In this project, the student designs an intricate facade for the ground floor of an urban building situation, providing a new identity and a more spatial quality. Sheets of transparent acrylic glass are laser-slotted along parallel lines for the prototypes. In addition, different transparencies and textures are created by laser-scoring. The individual slices are deformed by a tool consisting of three pins, which deforms three of the slices at once, thus creating openings. Different shades of transparency and reflection become visible, depending on light conditions, view-angle and apertures. These prototypes can be interpreted on different scales - either as a building element, or as a scale-model of a larger shaped surface. The effect of the laser-scored surface works very well as texturing and light filtering (Figure 6).

- Laser pattern: score, slot
- Deformer tool: 3-pin
- Robot movement: push

Case study 2: The Cube
The design intention of this student was to create individual facade perforations and apertures, for the four differently oriented sides of a house. The selected cut and form pattern depends on different demands of light filtering and views to the outside. The project combines triangular perforations with linear, pushed-out openings in different depths and angles. Opaque acrylic glass is used, and the final prototype consists of four panels combined to a cube. Surprising in this case study is the greatly achieved effect
of different transparencies, apertures and reflections. The geometry created by the deformation depends on the contact point of the push-tilt-movement in relation to the length of the slot. Therefore, the openings acquire intriguing irregular shapes (Figure 7).

- Laser pattern: perforate, slot
- Deformer tool: half-sphere
- Robot movement: push, tilt

**Case study 3: Floral Explosion**

The design intent of this project was to create an organic (floral) appearance from rigid base geometries. Scoring and cutting is combined in a sophisticated way: diagonal cross-shapes are slotted to create openings through deformation, and square patterns are scored on the "underside" of the panel. These special scores are designed to influence surface deformation when pushed against a pyramid shape, to achieve a planned square edge-condition between the different deformation fields (Figure 8).

- Laser pattern: score, slot
- Deformer tool: pyramid
- Robot movement: push, tilt

**Case study 4: Slit-Deformed**

In this project, the student experimented with laser-cut slits to create different geometries of deformations and apertures, merely depending on the robot's movement. A regular grid of a cross-shaped pattern is cut, and deformed by a truncated pyramid, comparing the geometric outcome of push-, tilt- and twist-operations. This study gives a lot of insight into the forming behavior of the surface, creating geometric variations depending on cut- and form-parameters (Figure 9).

- Laser pattern: slot
- Deformer tool: truncated pyramid
- Robot movement: push, tilt, twist

**CONCLUSION AND OUTLOOK**

This paper locates its research in the field of digital design, digital fabrication, and robotic technology, implementing material properties. It investigates robotic fabrication as a dynamic design process. A specially developed robotic design-fabrication workflow is described and explored in an experimental way, illustrated by four experimental
case studies. The created prototypes are appreciated as design and study objects. Reflecting on them, conclusions can be drawn on the potential of the presented workflow for similar design-fabrication processes, implementing other malleable materials in a cut-and-form process. Furthermore, a big potential for specific applications in architecture is conceivable, like additive building skins or systems of primary skin structures.

The next steps in this line of research will be the exploration of more complex robotic deformation movements for form-creation, as well as the establishment of a design catalogue created by the developed design-fabrication process.

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