Designing the Negative

An exploration of robotic fabrication for customized concrete formworks

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Abstract. *Designing the Negative was the title of a Master Studio that took place at the Institute of Architecture and Media of Graz University of Technology during the summer semester of 2012. Students designed and fabricated prototypes of customized concrete formwork as part of their studio assignment. The studio theme forced students to think about digital fabrication with parametric tools in a hands-on fashion. Using robotic technology and hot-wire cutting, students worked with the robot's constraints (size of the robot's arm, robot's axis and tool's restrictions) to design complex curved elements that could serve as formwork (the negative) for cast concrete elements (the positive). The students were asked to design a production strategy for their cast concrete elements as well as the application of said elements in an architectural scheme. The student projects confirmed the value of a pedagogy that takes on research-relevant questions in an interdisciplinary studio setting and engages students in a process that is best described as digital crafting: it simultaneously addressed the conceptual and technical as well as the material and tactile aspects of digital fabrication and design.*
Keywords. *Digital fabrication; customization; concrete; hot-wire cutting; parametric design.*

DIGITAL CRAFTING

"Buildings were once materialized drawings, but now, increasingly they are materialized digital information – designed with the help of computer-aided design systems, fabricated by means of digitally controlled machinery, put together on site with the help of digital lay-out and positioning devices, and generally inseparable from the flows of information through computer networks" (Mitchell, 2005).

In his keynote to the Caadfutures conference 2005 in Vienna, William Mitchell pointed out the manifold ways in which computers influence the design and construction of buildings. In his words, "constructing complexity" is what it's all about. If we only look at how using CAD tools speed up the design process or how digital fabrication makes certain forms more easily or more economically buildable, we are missing the bigger picture: the way these different computer-applications interact to create a paradigm shift: from materialized drawings to materialized digital information.

Preparing students for this paradigm shift means to not only expose them to the hardware available in digital fabrication, but to familiarize them with the entire sequence of steps from design to fabrication and to try to compress these stages as much as possible into one holistic design approach in which the digital design is mindful of the digital fabrication. Gramazio and Kohler refer to this approach as “informing material” (Bonwetsch et al. ,2006), thereby inverting Mitchell’s more conventional idea of materializing information. What’s notable about this inversion is that it gives the material a more prominent status.

The studio we present in this paper should be seen in this tradition. Rather than trying out some digital fabrication method as a purely technical exercise, we try to get our students to conceive of the design and production process as a whole. To get them to appreciate this we think it’s important that students actually digitally fabricate what they design, that they lay their hands on it, experience its material properties. We think of this as digital crafting.

BACKGROUND

Concrete is a homogeneous material that transfers its state from liquid to solid matter. A famous slogan about concrete that the German cement industry used in their advertisements translates to “It all depends on what you do with it” – implying an almost infinite formal freedom of their material.

This formal freedom is relative, of course, as it depends on a number of factors – a prominent one among them being the type of formwork that is used. It is in the production of the formwork that digital fabrication is starting to have an impact. But making customized formwork didn’t start with digital tools, It has been a topic in advanced architectural and structural design for many years.

Looking back into the history of architecture, we see that the work of Felix Candela, Pier Luigi Nervi and Iannis Xenakis, have showcased the use of concrete for the development of structures of complex geometry. Such references have served not only as inspiration, but also as case studies of material performance and have led to contemporary design experiments (Pronk et al., 2007a).

More recently there have been several novel approaches for the design and fabrication of customized formwork. One example is the research by Mark West (2009) on fabric formwork undertaken at the Centre for Architectural Structures and Technology (CAST); in this case, the use of formworks of flexible matter led to a combined strategy for form-finding and fabrication. Similar design experiments that test the limits of digital processes in design and fabrication are also undertaken at a number of architecture schools including for example the Architectural Association (Dourtme 2012), the University of Eindhoven (Pronk et al., 2007b; Huijben et al., 2009) or the ETH Zurich (Bonwetsch et al., 2010). In some of the mentioned cases the methods employed involve fabric or pneumatic structures, which typically act as “lost formwork”. Thus the possibilitity of reusability is not considered. Other examples use wooden formwork panels, which are CNC-milled or into which additional elements are inserted. As these examples show, the use of digital tools for design and fabrication has led design research in creating customized formwork towards new paths, that exploit the given technological tools, resulting in new concepts and processes from design to production.

DIFFERENT APPROACHES IN CUSTOMIZED CONCRETE FORMWORK

The conventional manufacturing of formwork for concrete is expensive, difficult and time consuming. Moreover, the handmade formwork has difficulty to fulfill the required precision and to deliver the geometries obtainable by contemporary 3D modeling software. Digital fabrication opens new possibilities in this respect. Using CNC-milling processes and materials such as wood, it becomes economically feasible to produce formwork with complex geometric shapes. Nevertheless, such milled formwork is still very labor-intensive and thus it is typically produced such that it can be used many times.

Formwork such as that used for the construction of the Mercedes-Benz Museum in Stuttgart by UN Studio or for the stair at the MUMUTH in Graz by the same architecture firm could not have been built without digital design and fabrication tools, even though the production of the custom-made formwork was still a highly labor-intensive construction that involved building the form out of wooden planks and then sheathing it.

The mentioned examples demonstrate that by using digital tools, forms of high geometric complexity can indeed be built, but they are also notorious for the high cost the construction of their concrete structures incurred. In the case of a prominent museum or music theater, this can be justified through the buildings' status as extraordinary public 'icons'. In more modest architectural projects extravagant formwork is only feasible when the forms can be used many times. Thus there are applications of custom formwork that is being used to create patterns of repetitive elements or modularized structures.

DESIGNING THE NEGATIVE: HOT-WIRE CUT FORMWORK

The hot wire cutting of Styrofoam as formwork has the promise of making even complex concrete forms relatively quick and cheap to produce. We have conducted a number of studies with this technique at our institute, including a seminar in 2011 (Stavric and Kaftan, 2012). As a follow up to these experiences, building on the knowledge gained and the methods tried out, we organized a full design studio around this topic in the following year. We called this Master Studio, which took place at the Institute of Architecture and Media of Graz University of Technology during the summer semester of 2012, "Designing the Negative".

The title refers to the unusual design thinking the class required from the students. When designing forms out of concrete, the final shape - the positive - is defined by a formwork - the negative - within which it is confined. The design of this negative was the focus of the studio. To produce the formwork students had to apply robot-controlled hot-wire cutting technology. Students worked with the robot's constraints (size of the robot's arm, robot's axis and tool's restrictions) to design complex curved elements. This led to structures of diverse scales that were negotiating with functionality, material use and performance. Since the hotwire cutting is so quick and simple, they could conceive of applications with highly individualized and complex formwork. We therefore challenged the students to approach the subject such that the reusability of their formwork was not necessarily the primary concern. The studio also involved in-depth and hands-on teaching and learning about parametric design, digital fabrication, as well as concrete construction.

The outcome of the studio exemplifies the great potential the use of robotic fabrication can have for customized concrete constructions responding to individually selected design briefs within a variety of architectural contexts.

DESIGN CHALLENGE AND HOT-WIRE FABRICATION

The design challenge involved processes closely related to the selected fabrication method. Thus the geometry should mainly be comprised of ruled surfaces for fabrication with a straight heated wire (Stavric and Kaftan, 2012) or surfaces that are the resultant of the proliferation of a section along a rail, for fabrication with a pre-shaped wire. Thus, already from the initial form explorations, students were aware of the design to production continuum, embedding the robot's constraints in the parametric design of the projects. At the same time, the understanding of material characteristics further constrained the design development. Concrete's structural behavior displays great performance and efficiency for compression structures. As the design challenge was by no means limited to the exploration of merely 'ornamental' design, programmatic, aesthetical and functional criteria all came into play, giving rise to a variety of structures and uses in an architectural context. While in earlier tests the students focused mainly on facade panels, in this studio they were asked to conceive of an overall structure and scenario in which this construction method could be applied.

The methodological approach involved specialized seminars on concrete performance and structural behavior coupled with introduction to parametric modeling and individual design tutorials. Students worked with 3D models and scaled prototypes resolving issues of modularity, jointing and construction while envisioning full scale structures of complex morphology. This hands-on experience was of great value as it provided feedback for both design and construction process, tackling among others the material economy, reusability of formwork, construction sequence and mastering of the techniques of concrete casting, vibration and finishing.

MODULARITY, PATTERNS, REPETITION AND LABYRINTH

In "The Self-Made Tapestry", Philip Ball describes patterns as "arrays of units that are similar but not necessarily identical, and which repeat but not necessarily regularly or with a well-defined symmetry" (Ball, 1999, p.9). Repetitive patterns and modularity were key concepts within the studio experimentation, as students were asked to consider the size restrictions of the available digital fabrication equipment in the design and fabrication of their projects.

There is an intricate relationship between the individual custom module and the assembly system. Parametric design however, succeeds to control the interaction among the local and global scale (component & assembly) as changes in the geometry, topology and joinery of one scale have direct implications on the other.

The projects displayed two levels of parametric modularity, related to the geometry, scale and construction system. We could distinguish the following:

1. Parametric modularity in the formwork only, where components of the formwork were assembled together before concrete casting (ex. "Murnockerl"),
2. Parametric modularity in the formwork as well as in the overall assembly (ex. "Birdspotting center").

Students developed repetitive structures and patterns, yet with subtle variations, displaying differentiation for specialization, in a dialogue between apertures, closed parts, connection nodes. The morphological and conceptual understanding of the labyrinth as an architectural form and symbol, served as a source of inspiration and a common starting line for design explorations within the broader field of non-standard architecture. In the spirit of digital craftsmanship the studio tries to foster, students were asked to not only develop their parametric models to the point that they could be fabricated by the robot, they also had to test their negatives by using them to cast the actual concrete elements.

STUDENT PROJECTS

The design task for the students was to come up with a system of cast concrete elements that takes advantage of the specific possibilities of the hotwire cutting in the preparation of the formwork and a showcase application for said system. The following three projects give an idea of the range of options students explored.

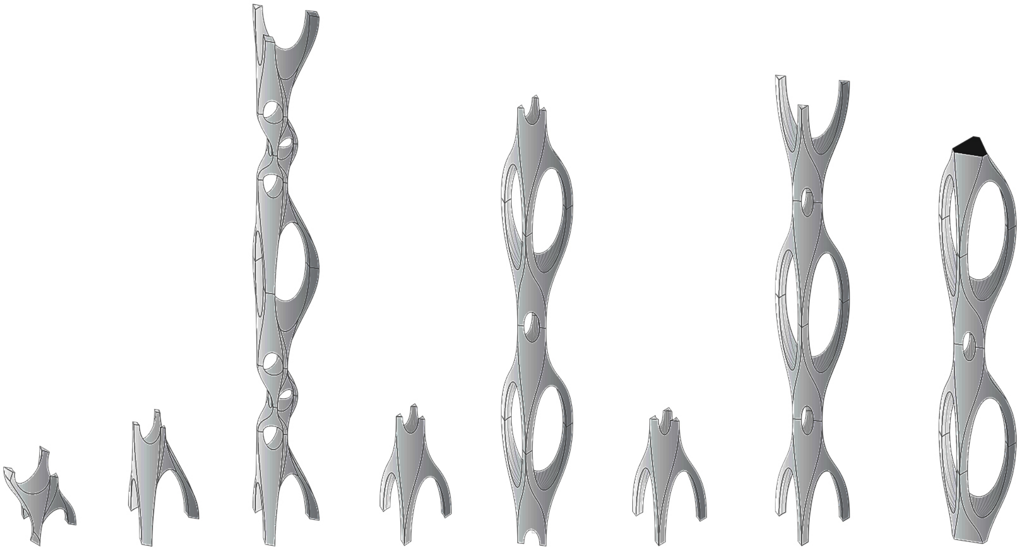
Birdspotting centre

This project by Alice Demenyi and Henrik Jonestrand explored a geometrically intricate form that could stack up to serve as a visual screen around a bird-spotting centre. Taking advantage of the parametric fabrication, each stacked element could have a precise height, such that the entire structure adapts to the uneven rocky topography of the Island for which it was proposed (Figure 1).

The stackable components are topologically based on an antiprism in order to achieve their structural stability. The n-sided antiprism is the result of rotating the base m by an arbitrary angle around axis a. Such a 3D form can be generated by twisting a cube around one axis that is parallel with four cube edges. In our case the geometry is based on either square antiprism, the anticube, or on triangular prismoctahedron (Stavric and Kaftan, 2013). The bottom base m and top base m1 can be connected by triangular faces which edges can be further modified by splines curve to generate different shapes (Figure 2).

Figure 1
Designed bird-spotting centre.

Figure 2
Different variations.



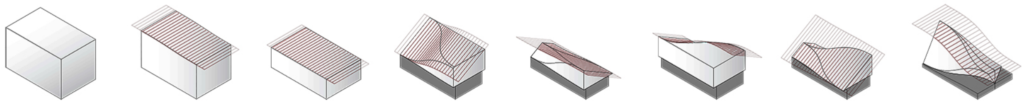


Figure 3
Robot cutting paths and order.

Therefore, the element can be formed out of ruled surfaces that can be fabricated by the straight wire. Inside of the antiprism the rotational paraboloid is parametrically generated and subtracted from it. Because the base and the top faces can be independently scaled, it is possible to create a variety of fluidly formed columns out of those stacked elements. Each cut can be done precisely and fast with minimum manipulation of the foam block between cuts (Figure 3) and there is minimal material waste from the cutting (Figure 4) .

Murnockerl

This project by Stefan Haad and Christoph Ringhofer proposed a type of urban furniture. The idea was derived from the large pebbles that are found in the river running through Graz, the Mur, which are called Murnockerl (Mur-pebbles). Each Murnockerl is based on a common parametric model which can generate a wide variety of geometrically different concrete shells. The parameters can be fixed based on environmental conditions, ergonomics and social behaviour (Figure 5).

The formwork of the shell is composed out of inner and outer formwork, each being an assembly of hexagonal parts. Each hexagon is further divided around its centre point into six triangles (Figure 6). The hexagons are not planar and this enables the cutting of each hexagon using only straight wires for both convex and concave parts. Each formwork part needs 6 to 16 cuts. However, the cutting can proceed very fast, because the cut XPS blocks do not need to change their position for each cut.

71° North

This project by Beate M. Hansen and Marit Oysaed proposes a shell concrete structure that is situated at a tourist hike in the far North of Norway. Unlike in case of the Murnockel project, the shell is not a singular cast, but an assembly of concrete elements. The primary hexagonal elements are stacked into arcs that are locked together by secondary quadrilateral elements (Figure 7).

The shape and varied thickness of the elements is based on structural analyses. Some of the primary hexagonal parts are shaped as light-funnels. The di-

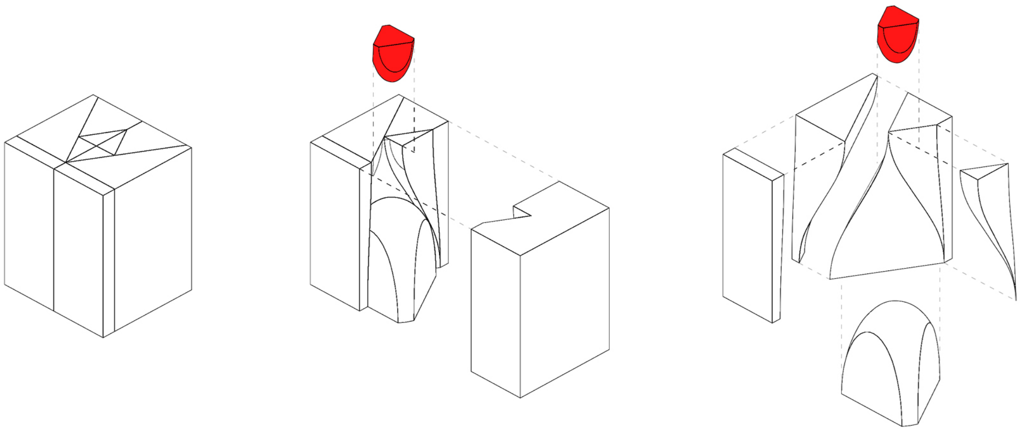
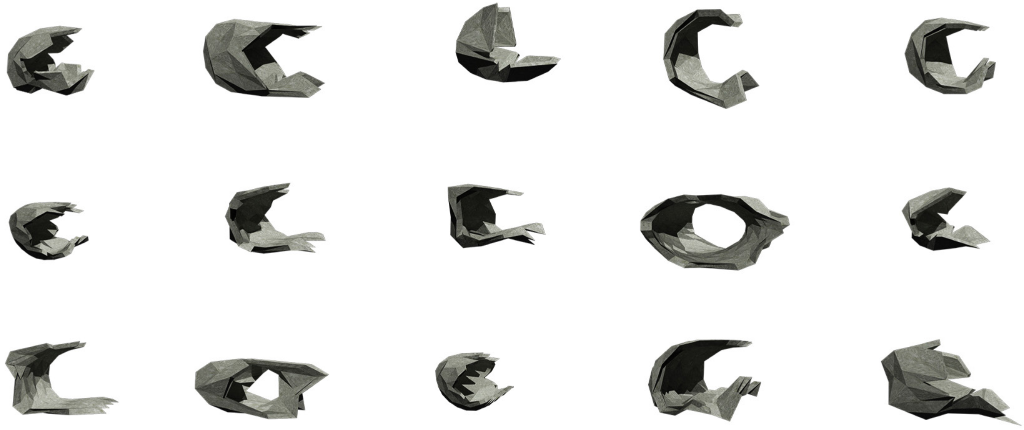


Figure 4
Assembly of formwork.

Figure 5
Form variations.



rection of the funnels' openings is based on the sun analysis and highlight the fact that at this location one can experience midnight sun during a part of the summer (Figure 8).

The formwork comprises of two parts. First, the hexagon is cut with straight wire.

In the last step the bent wire is used to cut the curved funnels (Figure 9).

CONCLUSIONS

Among the benefits of the described design and construction strategy is the fact that customized formwork can be built very quickly and efficiently with regard to material use, as it minimizes waste. Furthermore, one can achieve more flexible forms of prefabricated concrete, which opens up new possibilities and broadens the morphological vocabulary of prefabricated concrete.

Figure 6
Topology and structural logic.

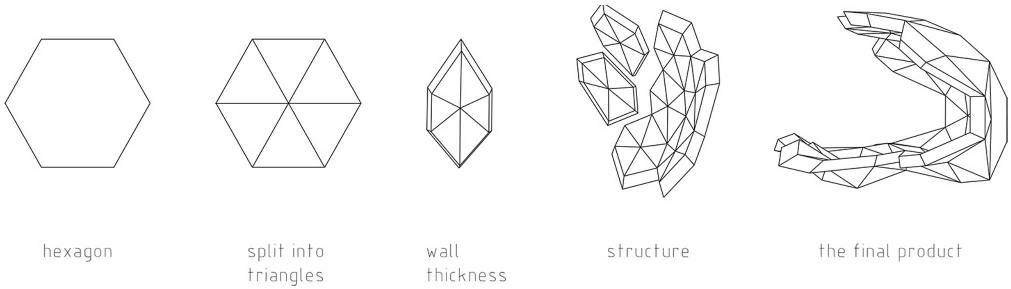
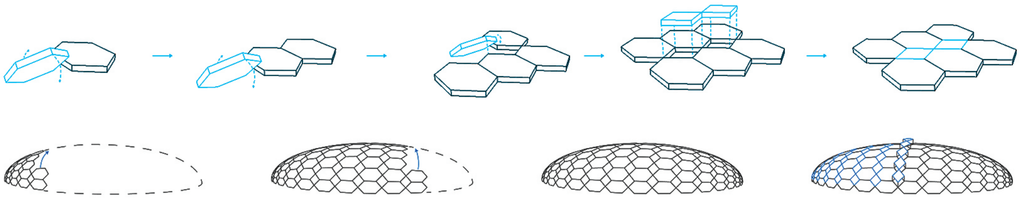


Figure 7
Topology and assembly logic.



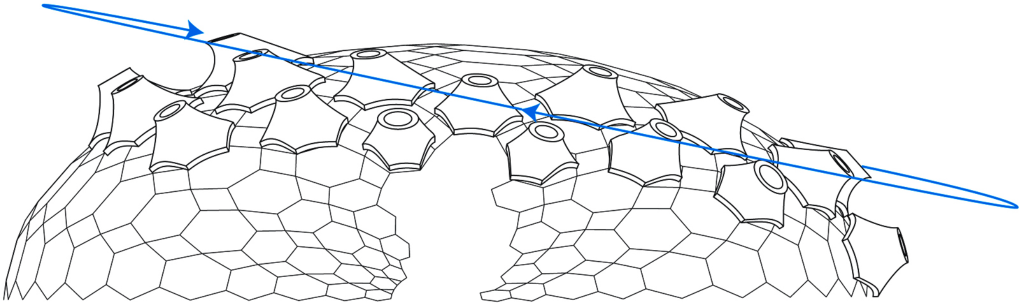


Figure 8
Final structure with oriented funnels.

The students explored these possibilities in their designs in a hands-on fashion, getting a feel not only for parametric design software, but also for robotic movements and for the pouring of concrete. Thus the studio gave them a thorough introduction into the inricacies of digital crafting. For most of them, as well as for the instructors, designing the negative was a very positive experience.

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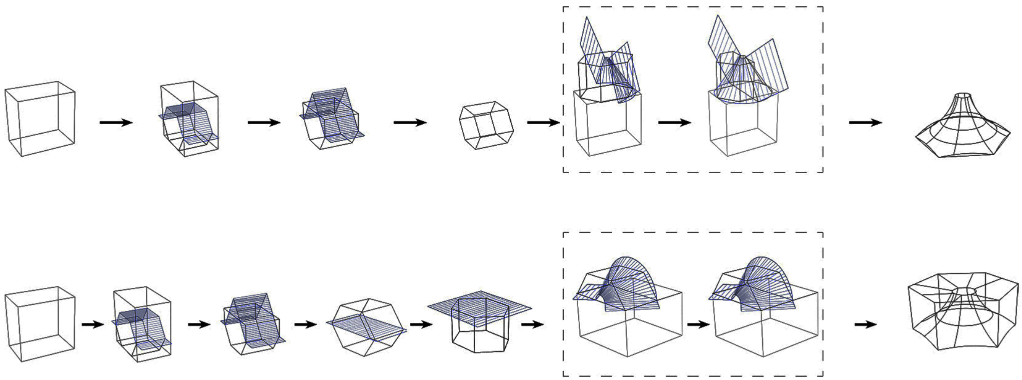

Figure 9
Robot cutting paths and order.

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