ROBOTIC PRODUCTION IMMANENT DESIGN

CREATIVE TOOLPATH DESIGN IN MICRO AND MACRO SCALE

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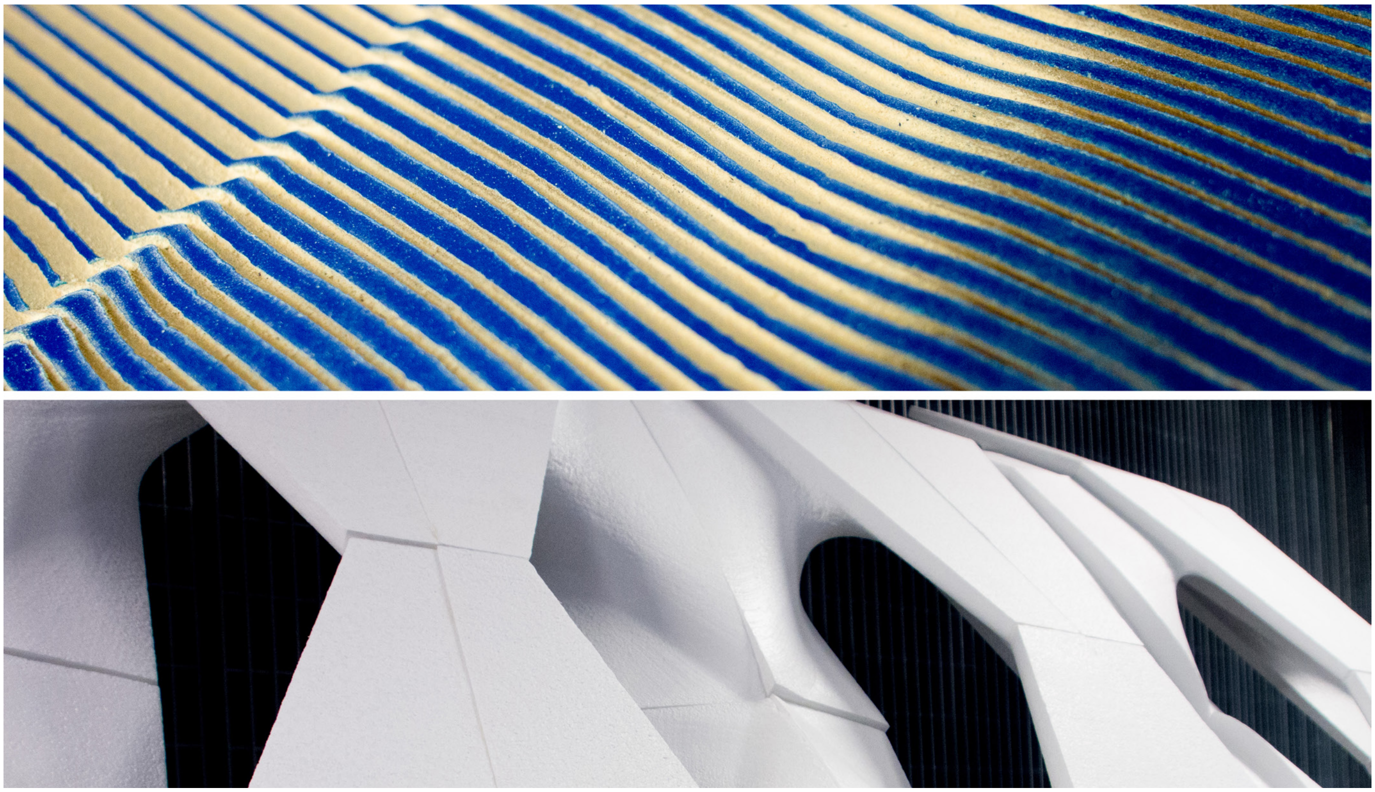


1 Complex surface micro structure appearing like a holographic 3D spatial structure. Created through multi-axis tool paths and a conical milling tool within five minutes (above). Spatial macro structure generated through material efficient hotwire-tool path layouts (below).

ABSTRACT

This paper elaborates on the concept of production-immanent design for robotic fabrication. Instead of fabricating arbitrary geometries using generic CAD-CAM (Computer Aided Design / Manufacturing) workflows, visual programming environments allow designers to intuitively create highly efficient structures that are specially optimized for the capabilities of robotic arms.

Our research into CNC (Computer Numeric Control) processes results in several approaches in both the micro and macro scales towards integrating the multi-functionality of kinematic machines into creative processes with the goal of liberating designers in their use of robots as design tools. Efficient processes that, at the same time, allow a high degree of customization will enable a new generation of designers to create innovative and individual products or even allow entire branches of industry to stay competitive with newly industrialized countries.

INTRODUCTION

Within the last decade, CNC fabrication has become an important research field not only for architecture but even more for robotic automation. Two major factors are responsible for this development in the automation industry: a) the overall CNC market is seen as a potential new business field for robotic manufacturers and estimated by KUKA at more than twice of the overall existing robotic market including automotive or aerospace industries, and b) the ease of programming of kinematic machines has been revolutionized in recent years through software that directly accepts G-code from generic CAM software (KUKA, 2012)–rather than robot code that offers more possibilities, but is also much more complex–but also through parametric programming strategies that were inspired by work from the creative industry. In this paper, we will discuss the potential of *customized* CNC fabrication that goes beyond CAD-CAM and its value for the new creative robotic design community.

Our research into *robotic production immanent design* (Brell-Cokcan and Braumann, 2010) focuses on utilizing the special properties of tool-geometries to create complex geometries with a minimum of machine-time and wasted material (Figure 1).

Today, given enough time, nearly any imaginable form can be fabricated using state of the art additive and subtractive fabrication methods such as multi-axis milling and 3D printing. In the case of milling, a significant amount of that time has to be spent in CAM software combining predefined milling cycles to achieve a balance between speed and surface finishing in addition to the pure machine-time of the router. Given that the initial CAD data is correctly prepared, 3D printing does not require much time for programming; however the process of depositing or solidifying layers of a fraction of a millimeter is inherently slow and therefore time-consuming.

By itself, production-immanent design is not necessarily faster than conventional fabrication workflows, as the rules and interdependencies of geometries have to be initially defined, for example, via nodes in a visual programming environment (see below). However, once the parametric model is established, it becomes possible to rapidly generate design iterations by adjusting the input parameters, instead of going through a lengthy CAD-CAM workflow for each variation.

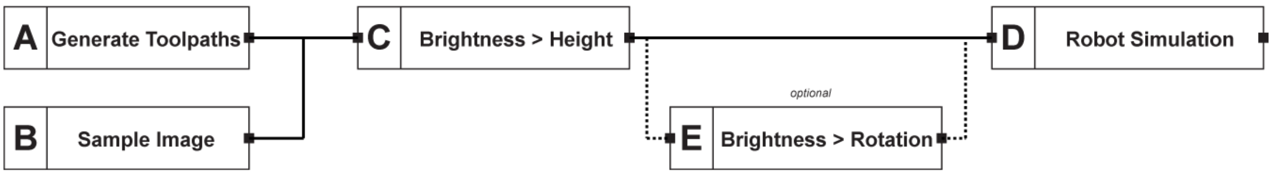
RAPID PROCESS PROTOTYPING THROUGH VISUAL PROGRAMMING

Robotic production-immanent design is therefore not so much a workflow for the fabricator that realizes a client's finished 3D data, rather than a process that has to be implemented by the designer in an early project stage. In return, it gives the designer the ability to move past the predefined strategies of CAD-CAM, to carefully consider and implement the properties of tools and machines. The speed of optimized fabrication processes enables a much quicker design validation as well as opening up the possibility of mass customization and web-to-real applications.

However, achieving such a speed requires an accessible programming environment where parameters can be quickly changed, the resulting data visualized, and the kinematic constraints of robotic fabrication implemented–so that any design *action* is immediately followed by a (virtual) robotic *reaction*, forming a feedback loop for quick iteration and optimization (Braumann and Brell-Cokcan, 2014).

The visual programming environment, Grasshopper, builds upon the CAD software Rhinoceros. *Parametric definitions* are created by linking nodes containing different functionality, from geometric operations to trigonometric calculations. Through additional plugins developed by the community, the scope of Grasshopper can be further extended. As the result of several years of research, the Association for Robots in Architecture's software tool KUKA|prc–parametric robot control (Braumann and Brell-Cokcan, 2011) adds specialized nodes that allow the simulation as well as the code generation for industrial robots, thereby linking machine constraints directly to parametric geometry.

One of the most significant advantages of visual programming over conventional programming is the possibility of intuitively grouping nodes into so-called clusters, which only expose the relevant input and outputs of the desired function (Davis et al. 2011). These modules can then be easily reused and recombined to create entirely new projects. As all clusters are part of a parametric chain, any changes are represented immediately, allowing a very intuitive and near-real time interaction with geometry and robotic fabrication.



2 Parametric patterns through functional clusters

MICRO-SURFACE STRUCTURES FORMED BY TOOL GEOMETRIES

In a series of research projects and hands-on robot-workshops, the authors have exposed a large number of international students, researchers, and professionals to the concept of production immanent robotic design.

The design and creation of "structures" informed by intelligent robotic tool-path design is spanning from "micro" scale surface structures deriving from tool fractures (see below) to "macro" scale where an efficient tool-path design results in spatial elements (see Section Highly-Efficient Spatial Macro-Structures). While the micro structures blend together to reveal larger scale patterns, the macro structures make up spatial, volumetric objects.

In the following sub-sections, three different approaches towards surface structures with increasing complexity will be presented.

THREE DEGREES OF FREEDOM: CONICAL MILLING

For the opening of the new headquarter of KUKA CEE, we designed a robotic installation that would create portraits of the guests. Initially, the idea was to capture 3D relief images using a Kinect sensor and to mill them out of polyurethane blocks. However, on-site experiments showed that the particular combination of robot and spindle could not fabricate more than three of these portraits per hour. The visual programming environment Grasshopper coupled with the robot-add-on KUKA|prc enabled us to develop and propose an entirely new application within just an hour. Instead of being captured with a Kinect sensor, a regular photo was taken and its grayscale values analyzed. Following a hexagonal grid, the robot drilled holes with a depth that is varied in relation to the brightness; for example, the higher the brightness value the deeper the hole.

On the spindle, a conical milling tool is mounted. Assuming a perfect conical geometry with a cone-angle of α degrees and a cutting depth of z mm, the intersection between the conical tool and surface of the polyurethane-block will be a circle whose radius is defined by:

$$z * \sin(\alpha) / \sin(90 - \alpha),$$

thereby enabling an extremely quick and reliable preview of the resulting structure. To make the difference between large and small pixels more apparent, a black top-coat was applied to the foam material.

The resulting process enabled us to fabricate ten panels per hour. Even though the absolute resolution (100 x 100 pixel) is significantly less than the Kinect's depth image (640 x 480 pixel), the high contrast makes the portraits seem photorealistic (Figure 3)–a process that is facilitated by the human brain's ability to detect known patterns and referred to as Pareidolia.

FOUR DEGREES OF FREEDOM: ROBOTIC CALLIGRAPHY

While conical milling utilizes only three degrees of freedom with movement in X, Y, and Z direction, the calligraphy project adds another degree of freedom, the rotation around Z. As even five-axis milling machines–being optimized for handling symmetrical tools–can only rotate around their X and Y axes such a project requires either the use of a customized four-axis machine or the flexibility of a six-axis robotic arm.

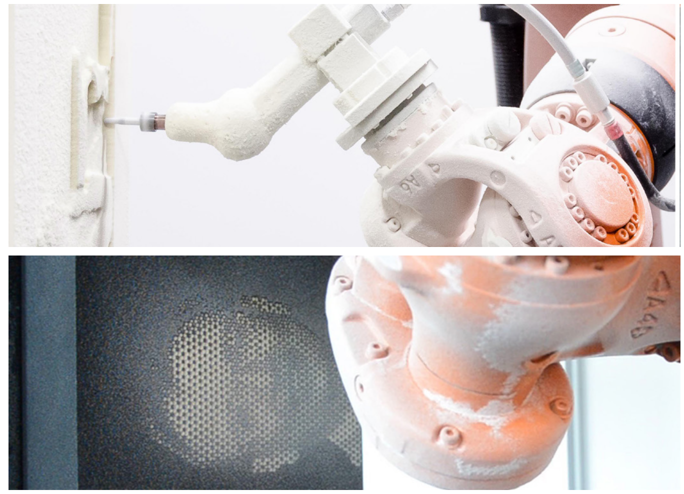
The project is based on the rectangular geometry of a calligraphy pen (Figure 4). Depending on the rotation around the pen's Z-axis, the resulting stroke can be extremely fine, very wide, or any value in between. For every point on a tool-path, the parametric definition queries the corresponding brightness of the source image and adjusts the rotation accordingly, with white resulting in a rotation of zero degrees and a very fine stroke and black requiring a rotation of ninety degrees so that a wide stroke can be achieved. In both cases, the origin of the rotation is set at the tangent vector of the tool-path.

In a workshop at Tongji University in Shanghai, participants were introduced to the concept of visual robot programming for the first time but were able to create their own parametric calligraphy designs at the end of the day.

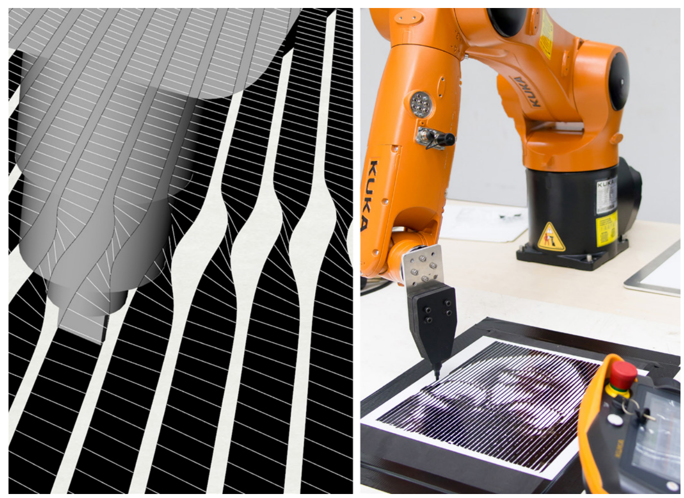
FIVE DEGREES OF FREEDOM: HOLOGRAPHIC STUDIES

In the previous two examples the parametric input values have been linked to only one variable, the Z-height of Conical Milling and the rotation around Z of Robotic Calligraphy. Advanced examples, prototyped at the University of Sydney and Bond University in Gold Coast, instead resulted in highly complex relationships that utilize the full kinematics of a robotic arm.

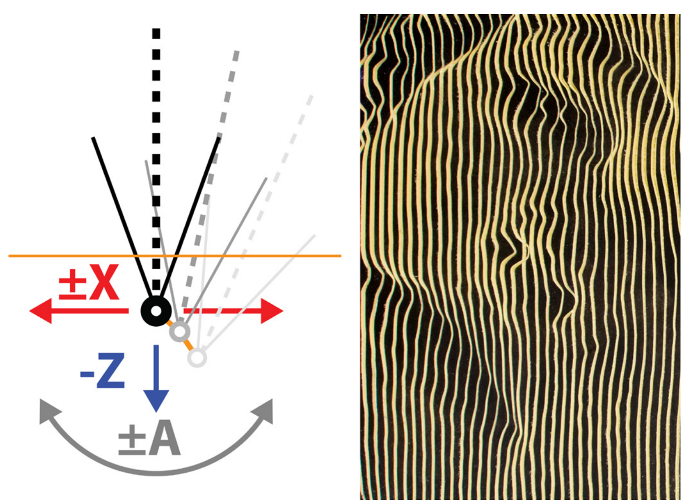
A conical tool is adjusted not only in height but also in its inclination resulting in ellipses at the intersection between the work-piece surface and tool. Unlike the three-axis conical milling, the structure underneath is not symmetrical and therefore significantly influences how the surface is perceived from different angles in space. Especially when moving around a panel that has been structured in such a way, we can observe a holographic effect that makes a planar panel appear like a spatial structure (Figure 5).



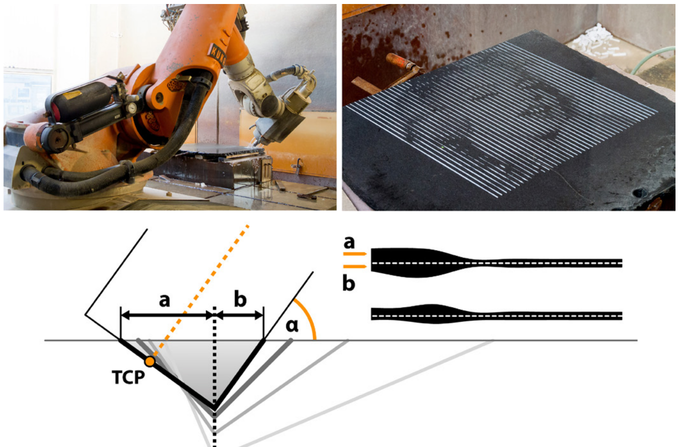
3 3D milled relief based on Kinect 3D-scanning data (top), abstracted portrait using conical tool (bottom)



4 Robotic calligraphy project utilizing the geometry of a calligraphy pen at Tongji University, Shanghai



5 Holographic surface structuring effect through three geometric parameters defined by an image sampler: ± offset in X direction, ± rotation A, -Z depth



6 Surface structuring of natural stone using cylindrical tools, KUKA KR500 heavy-duty robot milling black, polished granite. Given two brightness values a and b on either side of the cut and the diameter of the cylindrical tool, we calculate the position of the tool center point TCP and tool angle α, ensuring that the lower edge of the tool stays on the center-line of the cut

FIVE DEGREES OF FREEDOM: STONE SURFACE STRUCTURING

As part of a current research project, the authors are working with both industry and research partners towards establishing new fabrication processes and workflows for the surface-structuring of stone elements–a process that is currently done manually, for example, via chiseling–and where Europe is rapidly losing competitiveness with newly industrialized countries. As a first prototype with commercial viability, the idea was to evaluate multi-axis milling, because several heavy-payload milling KUKA-robots at research partner Bamberger Natursteinwerke's facilities were already being used for the CNC processing of stone.

However, due to the material properties of natural stone as opposed to wood and foam, no conical tools are available for such purposes. Even comparably soft sandstone is highly abrasive and quickly wears down any sharp edges and tips. Due to that, milling tools for sandstone have got a very simple geometry, consisting of just a diamond-brazed cylindrical rod with a grove, which does not act as an edge, but only to transfer material out of the cut. Even with such a simple geometry, tool-length is still continuously lost, necessitating the re-calibration of the tool before each job.

Due to these fabrication constraints, we had to find a new strategy for creating similar patterns without a conical tool geometry. As the surface structures are largely linear, the initial solution was to simply rotate the tool by forty-five degrees, resulting in a conical tool with an angle of ninety degrees and a usable depth of $d * \sin(45)$ mm, thereby creating a gap between zero and $d / \sin(45)$ mm, where d is the diameter of the tool.

Rotating the tool by forty-five degrees and adjusting the depth of the cut by the brightness value of an image result in symmetrical cuts that did not perfectly represent the given images, especially at high-contrast edges between black and white. While we initially visualized the predicted result after the generation of the toolpaths, we now followed the reverse strategy by first defining the edges of each cut with an algorithm that would not only take the brightness of one pixel, but also the values of the adjoining pixels into consideration. When looking at a section that is normal to the direction of the cut, we get two points at the edges and a central axis onto which the tip of the rotated tool moves along. Using this data, we can calculate the dynamic offset as well as tool angle (Figure 6). With a feeding speed of 0.015 m/sec using a thirty-five kW milling spindle the surface pattern prototype was finished within thirty minutes.

Following the success of the initial result, another test was commissioned, though this time using polished, black granite – a much denser material that greatly taxes both tool and machine. Even with a high-end, expensive cutter with modular blades, we could only achieve 1/5th of the velocity of natural sandstone, making it only relevant for very high-end interior-design applications.

HIGHLY-EFFICIENT SPATIAL MACRO-STRUCTURES

The projects showcased in Section Micro-Surface Structures formed by Tool Geometries show new approaches towards using tool geometry as a design parameter for the application of (spatial) structures onto the surface of planar panels. However, the concept of production immanent design is not limited to panels, but can also be applied to complex, 3D structures, for example by utilizing the special properties of ruled and/or developable surfaces or by developing entirely new fabrication processes.

In a design studio focusing on on-site, robotic fabrication–co-taught with Iva Kovacic and Rüdiger Suppin of TU Vienna's department for Industrial Building and Interdisciplinary Planning–David Schwärzler developed a process that creates sand-molds through a hollow-tip, angled tool. Compressed sand is loosened by the sharpened tooltip and then immediately removed through the vacuum within the hollow tip, enabling a nearly material-lossless fabrication process as both the compressed sand of the mold as well as the subtracted material can be reused. Tool wear is also reduced because–unlike in the industry-standard milling of sand molds (López de Lacalle et al. 2011)–the hollow tool is not rotating. As part of a reconstruction effort as well as physical proof of concept, a mold of an owl's head and 3D-scanned from the façade of the Secession, an iconic Art Nouveau building in Vienna was fabricated and cast into plaster. Together with civil engineers, the students evaluated the entire process and proposed a mobile construction unit that would contain all necessary fabrication steps within a few shipping containers (Figure 7).

In previous research (Brell-Cokcan and Braumann, 2010) we proposed the use of flank-milling (Figure 8) towards creating elaborate objects with hardly any material waste. One of the main limiting factors in that regard is the complexity of the effect that imparts the geometry of the tool onto the resulting geometry of the work-piece. In an idealized model, cutting along the surfaces with a tool with zero thickness would create ruled surfaces and elements that can be seamlessly stacked. In physical space, where every object has a certain thickness, the radius of the tool leads to the problem that with an increased inclination (β), the amount of removed material increases by a factor of *1/cos(β)* and the surface geometry turns into a mathematically doubly-curved surface (Li et al. 2007).

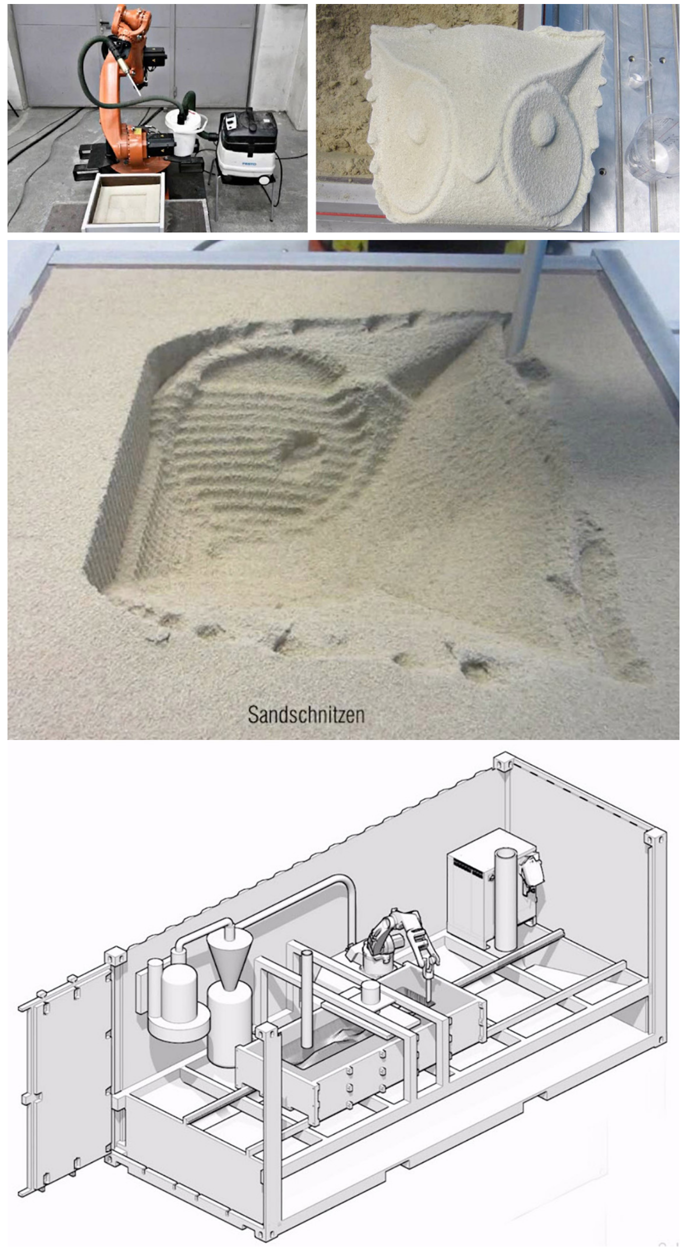
RULED SURFACES VIA WIRE-CUTTING

Wire-cutting is a process with many similarities to flank-milling, but geometrically much easier to handle when the wire is assumed to have zero-thickness. While this is technically not correct–typical hotwire-diameters are 0.5 mm–the value is low enough to be absorbed by typical construction tolerances in the area of architecture and design.

For an experimental robot workshop at RMIT in Melbourne, Australia, we had five days to design and fabricate a spatial structure out of EPS blocks with a minimum of wasted material. Due to its geometric properties, hotwire-cutting was expected to allow us to shape a maximum of material within a minimum of time. Research into robotic wire-cutting applications has been ongoing for several years, with e.g. Brandon Clifford's and Wes McGee's fifty-foot Periscope Tower having been built within a $5,000 budget out of wire-cut foam parts (Clifford and McGee 2012). Wes McGee et al. (2012) also found that wire-cutting offers significant savings in machine time, with, for example, a hyperbolic surface needing more than ten hours CNC machining time, but only a few minutes using wire-cutting.

While a concept is usually developed through (digital or manual) sketches, wire-cutting processes offers the advantage that they can be prototyped manually, just by moving a block of foam material through the hotwire.

Through this experimentation, Cam Newnham developed a highly intelligent system that consists of just three cuts–two cuts to give each short side a varying angle and one large cut diagonally through the work-piece that divides the block into two separate parts.

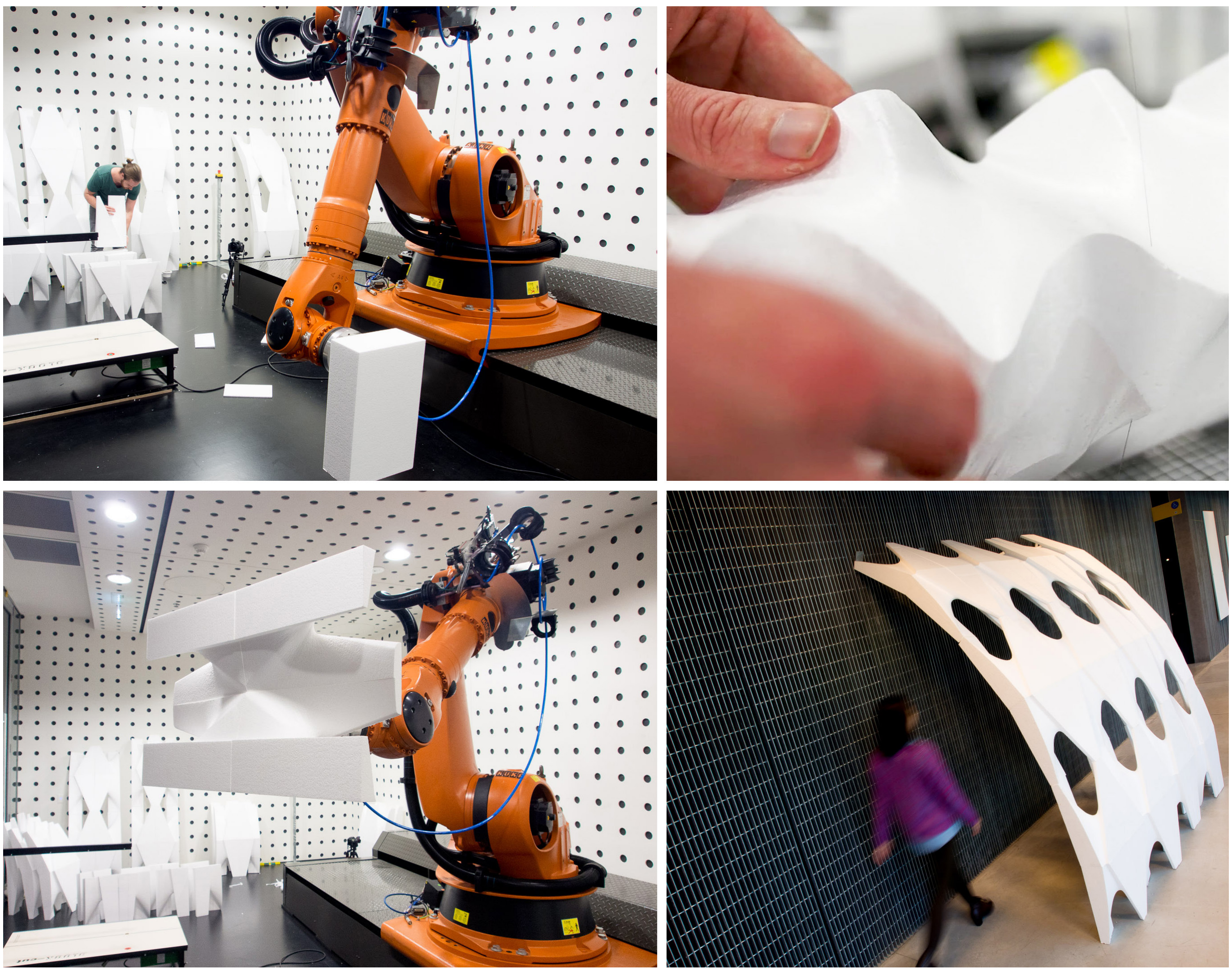


7 Re-usable sand-mold created through a custom hollow-tip vacuum tool. Proposed mobile fabrication unit within a shipping container (lower)

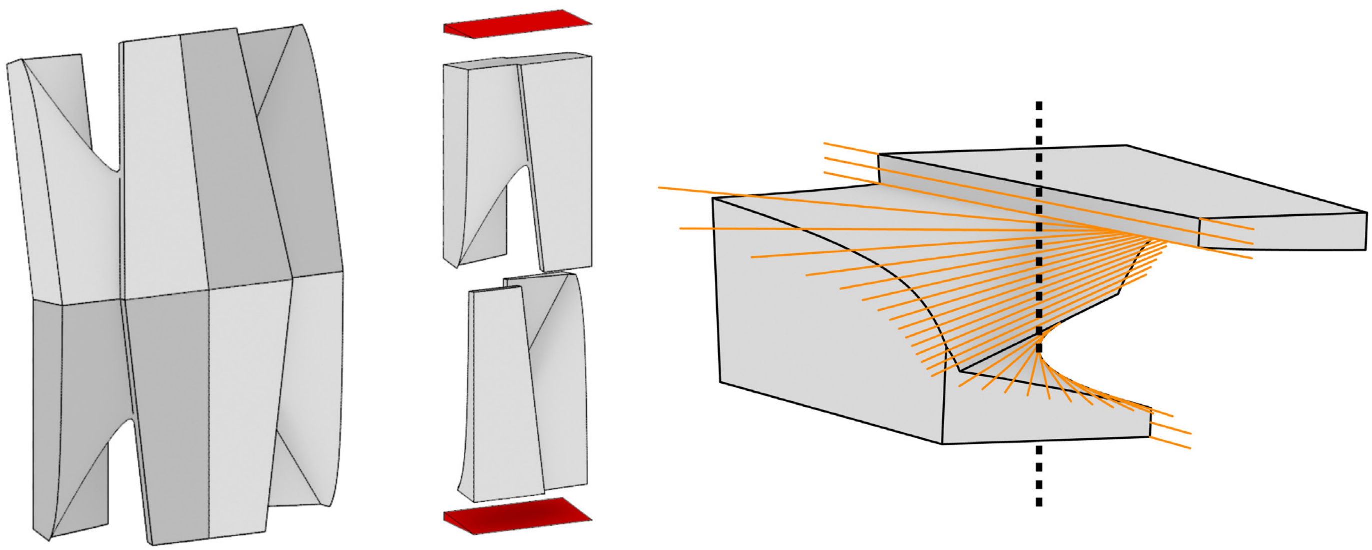
Two blocks–for example, four elements–make up an individual panel that can be assembled into a wall structure. The inclination of the structure is defined by the two initial cuts, while the second cut defines the parametric opening, making every piece individual (Figure 9).

Using Grasshopper, the developed strategies were turned into parametric definitions that allowed the students to create design iterations much more rapidly and with a more structured approach. Due to their geometric properties, wire-cutting processes can quite easily be defined, as the wire always has to coincide

8 Highly-material efficient fabrication of spatial structures through flank milling in 2010.



9 Highly efficient spatial structure at RMIT, Melbourne. The robot grasps a block of EPS and moves it through a hotwire (upper left), as manually prototyped before (upper right). Assembled diamond element (lower left), fully assembled structure (lower right).



10 Geometric block layout and segmentation. Similar colored elements originate from the same stock model, waste material is marked in red

with the rulings of the cutting surfaces–using the robot's six degrees of freedom, it is even possible to rotate the wire-cutting assembly around the ruling to optimize reachability. For this project, KUKA|prc was used to control and simulate the fabrication process. Literature also shows wire-cutting projects using supermatterTools (Pigram and McGee 2011), HAL (Schwartz 2012) and PyRAPID (Feringa and Sondergaard, 2014).

When programming such processes in CAD, it is usually assumed that the workpiece is fixed and a tool moves along the programmed path–therefore, each position is defined in relation to a coordinate system. As such, it is also possible to flip that relationship through an inverse transformation, making the tool static and having the workpiece mobile.

This inversion of the relationship between machine and tool becomes necessary as all sides of the stock-model are cut, so that no planar contact surface remains. However, it also offers additional benefits, as it enables us to directly couple the fabrication process with the final assembly, without having to change tools–something that would not be possible with commercial wire-cutting machines.

WIRE-CUTTING WORKFLOW

Using a flat vacuum gripper, the robot tightly grasps each block of material and moves it three times through the hotwire, first trimming the short sides according to the angle of the designed vault and finally performing the main cut through the diagonal of the block. Using this intelligent segmentation of geometry, each block of EPS yields a regular and a mirrored piece, requiring two blocks/four elements for each diamond macro-element (Figure 10). By considering the geometric constraints of wire-cutting we managed to create a design that loses only 4 per cent of its volume as waste, opposed to 52 per cent if milling were to be used.

As observed above, the main challenge is the translation of a mathematically "perfect" model into a physical object. While we considered the hot wire to be moving along the rulings of the surfaces, the resistance of the EPS material actually causes the wire the bend. To counteract the drag of EPS, it would be possible to increase the heat or slow down the robot, which would then lead to a much wider cut and further geometric issues when the cutting width approaches several millimeters. As such, a balance had to be found between the parameters speed and heat. Finally, 12 individual diamond macro-elements consisting of a total of 24 EPS-blocks were fabricated, with each block taking around 200 seconds of machining time. Therefore the partly manual assembly of the final structure proved to be more time-consuming than the streamlined robotic fabrication itself.

RELEVANT RESEARCH

A similar approach towards coupling wire-cutting with assembly has been explored by ETH Zurich as part of a workshop titled "Explicit Bricks" at smartGeometry 2010 and the DimRob research project (Helm et al. 2012). However, the focus of these projects lies on the on-site fabrication, for example, by using a mobile robotic arm for DimRob, rather than the rapid development of a highly material-effective system.

Focusing on efficiency, (Bard et al. 2012) used a robotic wire-saw to cut matching ruled surfaces from top to bottom of a block of semi-cured plaster that could then be assembled to a larger element.

CONCLUSION

We believe that the consideration of fabrication constraints through robotic production immanent design has got significant potential in both an industrial as well as a creative context. As part of a research project funded by the European Union's FP7 program, the authors–in cooperation with the natural-stone company Bamberger, robot manufacturer KUKA, robot integrator Klero, the architecture office Il Architects int., tooling expert Gibson, and research partners TU Dortmund and Labor–are developing new strategies for structuring stone surfaces, building upon the knowledge of robotic production immanent design generated by the projects presented in this paper.

At the moment, Bamberger is already using heavy duty KR500 milling robots to shape large slabs of sandstone, which are then post-processed and structured manually by stone masons. Through the research project, the consortium will develop both new hardware and new software workflows based on visual programming with the goal of establishing new fabrication processes that increase the competitiveness of the European stone industry against newly industrializing countries.

Similar gains can also be expected when such strategies are applied in a smaller scale within the creative industry. Being able to offer highly individualized products without significant extra costs will allow, for example architects, carpenters, and interior designers to compete with much larger, traditional firms. In a previous project, the authors worked with the Swedish company Absolut to promote a limited edition of Absolut Vodka by offering T-shirts that were customized by applying an abstracted portrait of the owner through robotic spray-painting (Braumann and Brell-Cokcan, 2014). There was significant commercial interest in the application towards creating a web-to-real application on a much larger scale. On a larger scale, KUKA|prc enabled the artists Neugebauer and Kölldorfer to robotically realize a 17m tall monumental sculpture out of 84 unique molds that now acts as the Red Bull Formula 1 track's landmark (Brell-Cokcan and Braumann, 2013).

We believe that a careful evaluation of processes in regards to both machining and programming time–especially outside of an academic context where these properties are often less significant–is crucial towards establishing new, robotic processes and towards proving that robotic arms offer a significant value that goes beyond their aesthetic appeal.

As such we expect that multifunctional machines and flexible software, along with rather recent developments such as web-to-real and other internet-based distribution and promotion channels, will open up entirely new business models for the creative industry.

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IMAGE CREDITS

All image credits to the Association for Robots in Architecture.

SIGRID BRELL-COKCAN AND JOHANNES BRAUMANN founded the Association for Robots in Architecture in 2010 with the goal of making industrial robots accessible to the creative industry. Towards that goal, the Association is developing innovative software tools such as KUKA|prc (parametric robot control) and initialized the Rob|Arch conference series on robotic fabrication in architecture, art, and design which–following Vienna in 2012 and Ann Arbor in 2014 – will be held 2016 in Sydney. Robots in Architecture is a KUKA System Partner and has been validated as a research institutions by national and international research agencies such as the European Union's FP7 program. Currently Sigrid is holding the first international professorship for creative robotics in industrial design at the University of Art and Design, Linz. Johannes is research fellow at the Austrian Academy of Sciences and heading the development of KUKA|prc. Their work has been widely published in peer reviewed scientific journals, international proceedings, and books, as well as being featured in formats such as Wired, Gizmodo, and RBR.