Digital Design to Digital Production

Flank Milling with a 7-Axis CNC-Milling Robot and Parametric Design

Sigrid Brell-Çokcan[1], Martin Reis[2], Heinz Schmiedhofer[3], Johannes Braumann[4]
[1,4]Institute of Architectural Sciences, University of Technology Vienna, Austria,
[2,3]Institute of Discrete Mathematics and Geometry, University of Technology Vienna, Austria
[1,4]http://www.iemar.tuwien.ac.at, [2,3]http://www.geometrie.tuwien.ac.at
[1]brell-cokcan@iemar.tuwien.ac.at, [2]reis@geometrie.tuwien.ac.at,
[3]schmiedhofer@geometrie.tuwien.ac.at, [4]johannes.braumann@tuwien.ac.at

Abstract: *Just recently Flank Milling has opened up new possibilities in detailing large-scale architectural building envelopes. Whereas examples such as the Hungerburgbahn by Zaha Hadid show the application of Flank Milling at the end of the architectural manufacturing process, our research, in contrast, focuses on the implementation of constraints immanent to manufacturing techniques as early architectural design parameters. This process is explored by the help of generative modeling tools, to allow an intuitive design of freeform parametric curves and surfaces while at the same time obeying crucial geometric conditions. In this paper, we will focus on the "digital design to digital production" process on a 7-axis industrial CNC -robot.*

Keywords: *CNC milling technologies; robot-milling; parametric design; freeform surface; digital architecture.*

Motivation

Architects are confronted with numerous CAGD (Computer Aided Geometry Design) tools, which, by the use of NURBS and Subdivision Modeling, have vastly increased the possibilities in the area of geometric freeform modeling. The general use of CAD has accelerated the pace of the architectural design business. However, although CAD systems have kept pace with the development of CAGD methods, CAD tools still do not offer adequate solutions for linking architectural freeform design to the process of manufacturing and construction. The question arises how to efficiently break complex geometries down into constructible units. The implementation of architectural constraints within the context of these design tools remains unsatisfactory.

A successful approach lies in collaboration between architects and mathematicians. The vast research area of *Differential Geometry* (Pottmann et al. 2007a,b,c) offers new solutions for the rationalization of freeform structures by means of, for example, planar quadrilateral meshes (Brell-Cokcan et al, 2009) or developable surfaces. But even with a deeper geometric understanding, architects can hardly solve the problems of differential geometry on their own.

Another design approach for freeform architecture is to explore *Computer Numeric Controlled* (CNC) manufacturing methods (Kolarevic, 2001+2005; Schodek et al, 2004) such as CNC-bending, wire-cutting,

Figure 1
Centre Pompidou Metz (Shigeru Ban) (top); gluelam sections before milling (top left); 5-axis milling of gluelam girders (top middle); mounting of the girders on the building site (top right); Hungerburgbahn (Zaha Hadid Architects) (bottom); image courtesy: http://www.designtoproduction.ch, Th.Mayer (bottom right)

laser-cutting or CNC-milling and implement their inherent geometric properties as input design parameters. The understanding and generation of *Numerically Controlled* (NC-) data has become a major support for architects in the general design of *file-to-factory* geometry and freeform architecture applications (Scheurer, 2009; Brell-Cokcan, Comploi, 2005).

The employment of robotic systems for exploring manufacturing and material properties and the way these can be linked to geometry and design has been shown at the ETH Zurich, where "material and production processes inform design" (Oesterle, 2008; Bonwetch et al., 2007)

CNC-milling strategies in architecture

In general, a typical milling job consists of two steps: the *rough cut*, which coarsely removes material layer by layer, and the *fine cut*, where the tool-tip precisely processes the remaining part, thus producing the surface-finish. The latter is a trade-off between time and quality. The smoother the result, the more expensive the production becomes. This technique is typical of mold milling, which naturally involves large amounts of cut-off.

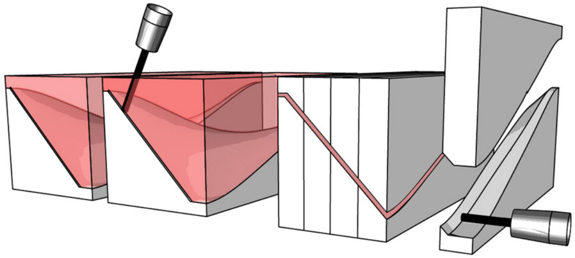
At first glance, *subtractive fabrication*, characterized by the removal of stock-material, in particular *CNC milling,* appears quite inefficient for large-scale applications in architecture, due to the substantial amount of material wastage (see, for example, the mold milling of the Neuer Zollhof Düsseldorf or the Kunsthaus Graz). Milling large surfaces with initial rough-cuts followed by fine-cuts is a very time-consuming process.

On the other hand, this technology also exhibits certain advantages, such as the so-called *just-in-time production*. Molds do not have to be stored for maintenance purposes. Instead, only the relevant digital data of the mold have to be kept and can be recalled and reproduced years later. Another advantage can be seen in the possible use of rather inexpensive materials such as wood, polyurethane or XPS foams for foaming inlays and molds, and the possibility of milling not only molds, but also final surfaces in high-end materials such as *Corian*.

Lately, milling also has been used in more sophisticated ways, aimed at the solution of architectural detail (Scheurer, 2009; Schindler, Scheurer, 2009).

The Hungerburgbahn project (Figure 1) by Zaha Hadid Architects shows a way of dealing with the connection of an arbitrary freeform building

Figure 2
Shop design (Baar-Baarenfels Architects) finished double-curved shelves (left); comparison between the strategy of rough-cut with a following fine-cut (middle); "waste-less" flank milling where both surfaces are used in the mold design (right).



envelope to its underlying, load-bearing structure. Special milled polyethylene sections fill the gap between the straight steel ribs and the arbitrarily shaped freeform glass structure. We refer to this strategy as *best fit milling*. A further possibility to be applied directly on wooden bearing members is to shape the structure itself through a final milling process according to the doubly curved skin, as seen at the Centre Pompidou Metz by Shigeru Ban, where 1800 double-curved gluelam girders were milled.

Flank-milling at TU Vienna

The goal of our ongoing research at TU Vienna is to waste less material in milling, to approximate freeform surfaces through the geometric definition of CNC- milling strategies- we refer to this as *best fit milling*- and to implement 6-axis milling with an industrial robot and an additional 7^{th} rotational axis (Aigner A., Brell- Cokcan S., 2009).

In cooperation with TU Vienna, in 2008 Baar-Baarenfels Architects (Figure 2) developed a shop design for Sportalm, an Austrian textile company, which was intended to be applied to all new stores. The design idea was an abstraction of snow-cornices that would function as a shelf system. The special, twisted geometry of the shelving allows the clothes to be cleverly displayed in a variety of different ways. Avonite/Corian was chosen as the main material, a massive and durable artificial stone that can be deformed with help of heat and pressure, guaranteeing a seamless look.

For the production of the twisted modules, consisting of four individual, agglutinated plates, oppositely shaped molds had to be milled out of MDF (medium density fiberboard) by a 7-axis milling robot producing ruled surfaces via a swarf-cutting job. These molds were then used to deform heated Avonite-plates under pressure.

Flank milling

In contrast to other milling methods, flank milling can use the whole cutting depth of the tool to carve material tangential to the surface to be produced, which exhibits several benefits: one single cut through the material produces the actual finished surface. Due to this, the stock material doesn't need to be coarsely removed in advance, thus omitting the *rough cut*. If not discarded, the second one can be used as well. A limitation, however, can be seen in the fact that this procedure always produces *ruled surfaces*, either torsal (developable) or non-torsal (depending on the way, the milling cutter is driven through the material), which means that such a surface is made up of straight lines. In general the property of ruled surfaces is very useful for architectural applications e.g. for covering freeform building envelopes with developable surfaces such as metal sheets. (refer to Gehry´s projects and for geometric properties Pottmann et al, 2007)

Flank milling in education

At TU Vienna, students are provided with a deeper geometric understanding of how ruled surfaces are *generated* and how they can be *produced*, from production, detailing to large-scale surface covering.

Due to the defined constraints of material and tool properties (refer to section 2), and in contrast to standard rough cut and fine cut milling technologies, *Flank Milling* can be seen as a rather interesting manufacturing technology for the experimental conception of large-scale freeform architecture.

For educational purposes, a major benefit is: Geometrically analogous production methods such as *laser-, waterjet-* and *flame-cutting* (Figure 3) are widespread in architectural manufacturing. While generally these techniques are intended to cut fully through a work piece, flank milling can additionally be constrained to carving the stock model according to predefined 3d-curves lying within the volume of the model-geometry.

Flank milled surfaces and the flank milling process can be employed efficiently by using end- or rasp-milling-cutters for the generation of one or two surfaces for each tool path, where the feasible cutting area depends on the cutting length of the milling-cutter along with the type of material to be used. The softer the material, the larger the area that can be cut off with a single tool path, the higher the feeding speed we can use and the less interference to be expected with the robot's dynamics. Materials such as extruded polystyrene foams (XPS) are therefore preferred for our educational set-ups.

The "digital design to digital production"-workflow

In our course programs "Architectural Geometry" - a cooperation between the Institute of Architectural Sciences / IEMAR and the Institute of Discrete Mathematics and Geometry - and "Digital Design to Digital Production" (Numerische Fertigungsmethoden) at TU Vienna, we foster students in the creation of their own, easy to use interactive *Design Tools* along with the implementation of *Manufacturing Parameters* as *Design Parameters.*

While real programming and scripting as a way of implementing geometric relations along with constraints such as development potential into common CAD-systems could be considered far beyond the scope of a standard architect's abilities, these demands have, however, lately been met by so-called "parametric modeling tools", allowing a user to easily define relations between geometric entities, rather than statically placing points in 3D space as seen in common CAD-modeling. These tools are, to a certain degree, capable of replacing programming as a process-driven way of defining and producing geometry within CAD-modelers.

For the following case study we employed *Grasshopper (McNeel)*, an evolving *generative design tool*, to allow the implementation of geometric manufacturing parameters while having design-results visualized at runtime. This workflow resulted in a *top down design*, allowing a maximum of creativity in the aesthetic design process while remaining close to freeform geometry, which, due to material and production constraints, was actually producible.

Following the design-process, generated *b-spline* data was imported into a CAM-Software (Hypermill/ OpenMind). After creating the tool paths for 5-axis *swarf cutting* (one of the flank-milling strategies implemented in the software) the NC-data was postprocessed and sent to our robot´s control unit.

Figure 3
5-axis flame-cutting of up to 200 mm steel-plates (left; centre); 3D node detail produced for projects such as Frankfurt Hoch Vier (Massimiliano Fuksas) or Zlote Tarasy, Warsa, (image courtesy by Waagner Biró); CNC-wire cutting at Steinbacher Dämmstoffe (right)

"StackIt" task

The design task was a set of parts to be (ideally seamlessly) stacked on top of each other, resulting in a smooth freeform wall-design. Given grasshopper as a parametric design-tool on top of Rhinoceros (McNeel), along with the theoretical knowledge from a previous lecture on surface-theory, the students were asked to elaborate a parametric model that would allow a user to design ruled surfaces (not necessarily torsal/developable) for the simulation of a flank milling process by editing various parameters.

These surfaces should be laid out parametrically, such that the successive design-process could be done freely while at all times automatically meeting the constraints prescribed by the chosen production process.

One set of mandatory parameters was provided by the dimensions of an XPS-block to be used as basic material, others were allowed to aim at, for example, the shape or angle of the wall-parts or various other parameters crucial to the individual designs.

When producing their parametric models, students had to take into account several constraints regarding design and production. One was the minimization of cut-offs. On the other hand it also was important to verify resulting cutting-paths/design in compliance with the feasibility of the milling process. To minimize the cut-offs, it was fundamental to lay out clipping-surface positions meaningfully. One flank-cut through the block naturally produces two surfaces which, if done intelligently, can both be used for the design. Milling of course removes material from the block, according to the width of the milling cutter, thus eventually detaching parts. If not taken into account, this fact can result in loose, unfixed parts, unable to undergo any further milling operation. Furthermore, as an important design factor, transitions of stacked wall-parts had to be seamless, but not necessarily curvature/tangency continuous, meaning that lower clipping-surface boundaries had to correspond to upper boundaries in some way.

StackIt results

In the developed Grasshopper files (Figure 4 and 5)created for the 'StackIt' task by the students, the main design tools of the user are the translation sliders for the individual control of the points, which define each curve for the cutting path. The primary curve is derived from a straight line along the y-axis with its length being equivalent to the XPS panel's length. Its control points are then shifted according to the individual values of the translation sliders. After that, the algorithm creates two copies of the initial curve, one of which is translated to the other side of the panel, while the other is again deformed by shifting the x-value of its control points with a slider. This happens in such a way that each cut (= pair of curves) defines two elements which are seamlessly stackable (G0 continuity).

To achieve horizontal G1 (tangent) continuity, the first and the last two control points are linked together and move synchronously. These geometric properties apply to the Grasshopper script, without taking the milling cutter's diameter into account. From the geometric point of view, when the milling cutter moves along a defined cutting path, two offset surfaces are created, which generally are not congruent. However, in the StackIt example where coarse materials and steep cutting angles are utilized, this deviation is mostly negligible. Solving this problem in larger scale projects would require the use of two separate cutting paths for each surface.

A real-time preview is implemented, which allows the user to drag a slider and see the corresponding reaction of both the stock model and the stacked wall without any delay. Besides the aesthetic live feedback, the parametric definition also calculates the highest cutting depth within a panel by measuring the length of lines which connect one parameter on the upper cutting curve with the corresponding parameter on the lower cutting curve. As the quality of the milling process decreases with the length of the tool - and tools beyond a certain length might not be readily available - this analysis immediately displays whether the resulting design of the

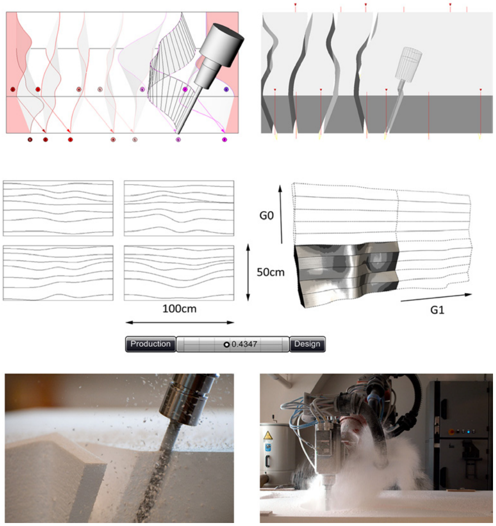


Figure 4
Layout of the parametric cutting paths achieving stackability (top left); preview of stockmodel (top right); live preview of Grasshopper generated manufacturing immanent toolpaths and panelsizes (centre left); StackIt preview of a possible freeform wall design (center right); flank-milling impressions of the 6-axis CNC-Milling Robot (bottom)

wall is feasible or not. If the cutting depth is too high, the user can either decrease the panel height (which preserves the formerly set curves) or adjust curves accordingly. Ultimately, the cutting paths and the panel-solid can be converted into regular Rhinoceros geometry (baked) and exported into the IGES format, which in turn can be processed by the CAM tool of choice.

Conclusion and future research

Our aim to direct students towards analyzing and rethinking complex freeform geometries in terms of manufacturing constraints was successfully achieved. Initially with little or no experience of the algorithmic nature of parametric design, at first some students had to struggle slightly with getting their first generative model done. However, due to the clear user-interface and intuitive handling, along with the Grasshopper-inherent dynamic visual updates of their designs, they soon realized and enjoyed the possibilities of a parametric design workflow. By implementing manufacturing limitations as initial geometry constraints, our students ultimately succeeded in generating feasible freeform-designs to be produced via flank milling.

In addition to the implementation of generative modeling we have started the process of rethinking CAD education. Due to our extensive research in freeform design (also refer to MLFS-project at TU Vienna, Pottmann et al, 2007; Brell-Cokcan et al, 2009) we have realized that most designs (even those from renowned architects) are lacking in terms of the capability of creating feasible freeform designs and segmenting and creating producable and constructible freeform-structures. Generally, machines work with simple geometric entities such as points, vectors, a number of axis and feeding speed. This kind of geometry can be analyzed and utilized in order to help architects in breaking down complex geometries.

The kinematics of the robot, however, are still hard to solve. We therefore see a major research area in exploring possible geometries within the

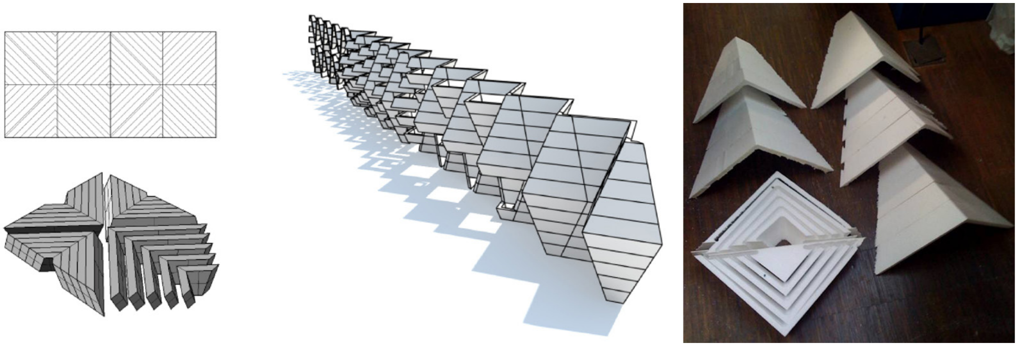


Figure5
"Planar" StackIt wall with minimized material wastage (Halvard Heskestad Waage and Bernhard Dal-Bianco)

non-cubic workspace and the robot's multifunction in industrial production.

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