Computer Numeric Controlled Manufacturing for Freeform Surfaces in Architecture

Sigrid Brell-Çokcan
Johannes Braumann

Introduction

Complex geometry and freeform surfaces have become a vast research area in architecture, mostly due to the recently attained 'ease' of design of freeform geometry in nearly all CAD (Computer Aided Design) software packages, where freeform surface design was originally implemented for the animation and automotive industry. However, generally CAD tools do not offer adequate solutions for fabrication, which means that most freeform designs are condemned to stay 'digital', without ever leaving the digital and virtual environment. Due to these interesting technical complexities, freeform 'built' architectural designs are still rare and therefore evoke intense emotions: one side appreciates their uniqueness and difference, whereas the other criticises them as being too stylish for common taste, too complicated to build, and therefore a waste of money.

In this text we will not discuss freeform design in regard to its architectural quality or effect on environment and people; instead we focus on its design and fabrication process and present our research and our work with students on developing strategies that enable 'digital' freeform projects to become 'real'. The fact is that nowadays nearly all architects have access to digital design tools and therefore have the ability to design 'free' form designs in much the same way as they design a straight wall. Our goal, therefore, is not only to equip our students and future architects with the capability of CAD design, but also to teach them how to develop their own digital tools and how to link their designs directly to CNC (Computer Numeric Controlled) fabrication in a bottom-up design approach.

Freeform Surfaces and the Development of Fabrication in Architecture – a Brief History

Complex geometry and freeform surfaces first surfaced in architecture with the earliest known dome-like human shelters built from wood and willow, discovered near Nice/Europe about 400 000 years ago.

Industrialization and improvements in the technique of manufacturing building materials such as iron and steel, or the invention of reinforced concrete in the 19th century (e.g. François Coignet *Béton aggloméré*, 1855), as well as new fabrication methods for glass panes at the beginning of the 20th century liberated architects in the expression of forms and styles in modern architecture.

In parallel a deeper understanding of structures and material allowed Antoni Gaudí (1852–1926), through the use of sophisticated physical form-finding techniques, to develop complex spatial structures informed by structural constructability and sculptural constraints alike. These multiple curved surfaces are prominently found in his *Sagrada Familia*, the construction of which started in 1882 and is still ongoing today. Rudolf Steiner (1861–1925) was the architect of the First and Second Goetheanum. These unique buildings (1914 and 1928) are early masterpieces in their use of doubly curved freeform surfaces in architecture.

Even though reinforced concrete seemed a good solution for the sculptural forms and wide-spanning free formed surfaces that peaked in the 1960ies, architects and engineers (e.g. Oskar Niemeyer or Heinz Isler) soon realized the limitations of this composite material for complex geometry that result from its heavy weight, the high costs of the formwork required, and the need for excessive man labour to fabricate reinforced concrete. One early attempt to solve aspects of these problems, for instance by reducing weight, was to segment the surface into structural members and cladding elements for the waterproofing layer. In 1914 the German architect Bruno Taut used reinforced concrete girders as the structural elements for the net vault of his well-known *Glass Pavilion*, with Luxfer glass bricks as the glazing elements. For Taut glass, the epitome of 'fluidity and sparkle', was the perfect material. Another successful example of a sophisticated prefabrication method is the segmentation of the concrete roof shells of Sydney Opera House as parts of a sphere (constructed 1957–1973 by Jørn Utzon).

The evolution from iron to steel offered engineers and architects new dimensions and various possibilities of prefabrication, assembly logistics and new material compositions for complex geometrical lightweight structures. Early protagonists were Buckminster Fuller, who is famous for his geodesic domes, and V.G. Suchov or Frei Otto, who are known for their suspended structures. One of the keenest utopias today is still the *City Dome*, a climate sphere covering New York City developed in the early 1960ies by Buckminster Fuller.

The knowledge of geometry in combination with new structural calculation methods has offered architects, in collaboration with engineers, useful approaches to sophisticated solutions for double curvature in manufacturing and fabrication. Examples are *Eladio Dieste*, known for his reinforced Gaussian brick vaults, Foster and Partners with their expertise in translational surfaces implemented at the *Sage Gateshead* (1997–2004), or Frank Gehry for his developable surface method deriving from his paper scaled models.

CAD/CAM: impact on Freeform Architectural Design

In the last two decades stylish building forms emerging from the deconstructive expression of architects such as Zaha Hadid (e.g. *Hungerburgbahn* in Innsbruck Fig. 1), or Coop Himmelblau (*BMW World* in Munich), were able to emancipate themselves entirely from geometrical or static constraints in their design, thanks to the easy freeform design of NURBS (Non Uniform Rational B-Splines) or subdivision modelling in animation software tools such as *Maya* or *3D Studio Max*.

The easy use of CAD in freeform design has made it more or less unnecessary for the designers to fully understand the geometric topologies of surfaces, the characteristics in the creation of surfaces, the quality of the necessary source curves behind the surface and curve commands. Up until now, CAD software developers have not provided users with relevant information, evaluation or analysis of the constructability or non-constructability of freeform surfaces in architecture. To give an example: the user cannot choose a surface command that ensures the fully automatic creation of developable surfaces such as Sir Norman Foster's translational surfaces seen at the *Gateshead*.

Fig. 1 ***top: 'Centre Pompidou Metz' (Shigeru Ban): glulam sections before milling; 5 axis milling of glulam girders; mounting of the girders on the building site;***
bottom: 'Hungerburgbahn' (Zaha Hadid Architects).

Fig. 2 *left/centre: 5 axis flame-cutting of up to 200 mm steel-plates; 3D node detail produced for projects such as 'Frankfurt Hoch Vier' (Massimiliano Fuksas) or 'Zlote Tarasy', Warsa; right: CNC wire cutting at Steinbacher Dämmstoffe.*

When we look back to Section 2 we notice that architects and engineers managed to build complex freeform surfaces before the CAD revolution of recent decades. So we ask: why do architectural software tools provide us with non-constructible arbitrary freeform surfaces? In our research at TU Vienna (see Pottmann et al 2007, Brell-Çokcan and Pottmann 2006) we have approached this problem in cooperation with mathematicians to reengineer and approximate arbitrary freeform surfaces. But is this a suitable solution for architects?

Geometrically highly complex, arbitrary, and therefore non-trivial freeform surfaces have to be approached in a different way so that they can be fabricated, transported and mounted. The question is: how can complex geometries be efficiently broken down into constructible units?

Digital Design in relation to CNC Fabrication

A good approach for constructible freeform design is to explore *Computer Numeric Controlled* (CNC) fabrication methods such as bending, wire cutting, laser cutting or milling, and to implement their inherent geometric properties as input design parameters. CNC fabrication is a mostly subtractive method, which means that material is removed, and it has become the most common fabrication method in architectural freeform construction (Fig. 1&2)

When it comes to real scale designs one major challenge is developing strategies for segmenting and dividing an object into producible units according to the machines' workspace, with an efficient toolpath design to make best of use of the material while minimising waste and machine time. If sufficiently understood, the general design of file-to-factory design and freeform architecture application using Numerically Controlled (NC) data can become a major support for architects (see also Scheurer and Stehling 2009). CAD software packages capable of linking the design directly to the machines are not yet available. Programmers and machinist have to break down and postprocess complex geometries into components such as *points, vectors, and toolpaths* – data, which, unlike freeform surfaces, can be understood by CNC machines. The goal in our teaching is to confront students with machinic constraints and to help in designing and implementing individual production immanent design tools via scripting or programming.

In this catalogue we can see different strategies of dealing with freeform geometry. The complexity of freeform design was solved by our students either by a clever use of CNC fabrication, such as laser cutting, 2D and 3D milling, hot wire cutting and robot manufacturing provided by the building workshop of the Faculty of Architecture, and/or parametric cleverness in digital freeform design. The fact is that all projects had to deal with the minimum of geometric entities: *points*, either to be used directly as input data for a CNC machine, or to parametrically define points in space with a certain logic. Generic CAD and CAM (Computer Aided Manufacturing) software used for architecture is, in general, not parametric, which means that the relations between object geometries are not defined. In contrast, parametric modelling tools such as *Grasshopper* work by the user declaring relations between (geometric) objects via visual programming by linking so-called components with each other. The output of one component, which can be seen as a container of data-information, is connected with and therefore defines the input of another component, which in turn can send data to yet another component. Therefore, whenever the designer changes the parameter of one object component, all the related (connected) objects change along with it.

In this catalogue the regular switch between physical and digital, between digital parametric and handmade scaled models helps to understand and explore the virtual designs and documents the struggle, failure and success of how to face the physical reality of the relation between geometric entities such as points in a complex 3D space. (Fig. 3) This strategy of a minimum of geometric information in 3D space via parametric points can be further informed digitally and physically to e.g. represent intersection points of curves, edges of a set of surfaces or even kinematic physical systems defined by the movement of points in 3D space.

For many students the projects exhibited in this catalogue mark the very first time that they had to leave the comfortable digital realm and were exposed to the physical realities of their evolved designs in real scale: from the choice of material, joints and structure, fabrication, and assembly to the resulting final objects.

The process of optimizing the designs according to the machinic constraints, material and time efficiency became crucial for realizing nonstandard freeform designs. Some projects explored machinic constraints in depth and used them as design parameters, therefore designing bottom-up for fabrication via parametric modelling tools. Implementing fabrication in the parametric model enables fabrication to react dynamically to changes in design, without requiring additional user input.

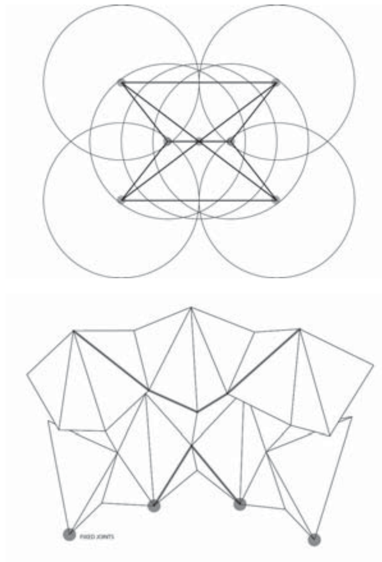

Fig. 3 ***Schematic design exploration and geometric relation of a set of points for the motion in 3D folding to be used as basics for the parametric model.***

CNC Fabrication and Results at TU Vienna

Many projects in this catalogue worked with sheet materials, such as polystyrene or acrylic glass, for their scale models which can be warm formed or deep drawn. To exactly control the material's deformation, moulds have to be produced in advance. (Fig. 4) This technology can be seen in many large-scale international projects, such as *Kunsthaus Graz* or *Neuer Zollhof* Berlin.

Fig. 4 ***Vacuum deep drawing at the model building workshop, material white polystyrene and polyurethane (mould).***

For sheet materials 2D cutting on the laser cutter and the 2.5 axis milling machine was extensively used by the students. One similarity between 2.5 axis milling and laser cutting is the ease of preparing data for 2D cutting, which does not require any special knowledge of CAM software. Instead, the input is two-dimensional curves saved as DXF and loaded to the machine controller. The order of the curves (toolpaths) to be processed or the change of processing between laser cutting and engraving can be defined by different layers in the CAD system, e.g. all folding projects had to develop their individual order between cutting and engraving the sheets of polystyrene. While the process of preparing data for 2.5 axis milling and laser cutting is similar, the laser cutting process is quite different, as one method removes material via high-intensity coherent light and the other one via a rotating milling tool. The complexity of freeform form shifts from the rather easy 2D preparation of data to a geometrically well explored geometric three-dimensional logic of assembly. The produced planar parts build up spatial 3D freeform structures as space definition and load bearing structure alike. The shape and layout of the parts must be well thought to reduce material waste and machine time. Generative algorithms aim to solve these so-called nesting problems and place as many objects as possible on a sheet of a given size. However, even these advanced algorithms are constrained by the basic geometry of the required shapes. For example, the *Plug&Play* project (Fig. 5) project has long, slender parts in the shape of an 'X' and managed to use only 40% of the plywood panel, while the *Ludic Pavilion* project used a more compact shape that achieved a noticeably better material/waste ratio of approximately 70%. The first prototype of the *Plug&Play* project was cut out of polystyrene using the laser cutter. However, for the final 1:1 scale installation, cottonwood plywood was chosen On account of

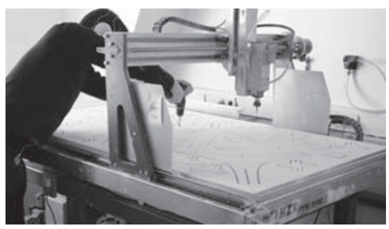

Fig. 5 ***3axis portal milling machine at TU Vienna***

Fig. 6 *Kinematic prototype of a set of 5 points*

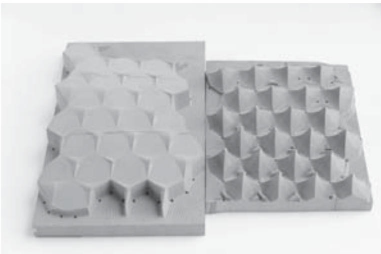

Fig. 7 *3D milled mould for deep drawing*

its larger workspace compared to the 2.5 axis machine, the students used the 3 axis portal milling machine to cut their 60 wooden panels. A 6mm milling tool was used for cutting the 6mm thick plywood in order to ensure the stackability of the resulting elements.

The fabrication for the bending and folding projects is done by laser cutting and, as described above, can be seen as an easy 2D process. The digital and physical three-dimensional control of the spatial and kinematic system, however, was a hard task to solve: all points had to move simultaneously without losing their geometric relations. Many projects were fascinated by exploring the possibility of motion, and one project managed to control the kinematic system digitally and physically alike (Fig. 6). Furthermore, this project used 3D milling and deepdrawing as CNC fabrication for the design of the individual parts.

3D milling (Fig. 7) is a more complicated process than 2D cutting. The designer does not just have to generate 2D curves as toolpath representation and as an output of their parametric model, but must either automatically generate machine codes or use commercial CAM software for preparing toolpaths. This is due to the fact that 3D milling does not just cut along a defined toolpath, but basically carves a defined geometric (freeform) object out of the stock material. The necessary motions of the milling tool are saved as toolpaths in machine code and executed at the machine. 3D milling was used for the pneumatic wall of the *Salzstreuner* project to fabricated moulds that were then used for deep drawing. First, the students generated a static geometry out of their parametric model and then sent the geometric data to the CAM software. After defining the size of the stock model, the machine and the tool properties, so-called milling strategies were assigned. These milling strategies define the way the machine removes material: A roughening strategy quickly removes material layer by layer with a large milling tool, while a finishing strategy works smoothly along the defined surfaces. Ultimately, toolpaths are generated and saved as a machine code for execution at the machine.

The material employed was polyurethane hard foam (also frequently used in the automotive design industry), as it is easier to mill than wood and, unlike other foam materials, is sufficiently resistant to heat. In the deep drawing machine, a heated plastic sheet is placed over the polyurethane mould and sucked downwards, the applied vacuum taking on the shape of the mould. After a cool-down period, the resulting plastic pieces were then used for the scale model. Due to their common geometric constraints, the deep drawing process and the 3 axis milling go together very well, as 3 axis milling cannot process any undercuts, and deep drawn plastic is not flexible enough to be sucked into the undercuts.

3D wire cutting machines are not commonplace in architecture, even though the manual hot wire cutter is one of the premier tools of architecture students. The advantages of wire cutting are the smooth finish and the large 'tool' length, while the restricted choice of materials and the restriction to geometries consisting of ruled surfaces are definite drawbacks. The *Inside Out* project (Fig. 8) was developed exclusively with wire cutting in mind, by first generating a parametric model that cuts a cube according to defined rules and then manually cutting the resulting pieces. For design exploration, only physical prototypes were used until the final polyeder layout was found. In fabrication, some methods have physical limits: one may be able to mill a 1:10 scale model using a 10cm milling tool, but there just are not any 100cm tools for milling a 1:1 prototype. However, hot wire cutting is relatively easy to scale, from portable to industrial size machines. Therefore, a 4+1 axis hot wire cutter was used for the 1:1 scale project, which controls the start and endpoint of a hot wire with two axes each and cuts through a stock model that can optionally be placed on a turntable. Numeric control is established by creating a DXF file that contains the movement of the start and endpoint of the hotwire as polylines. Therefore, the main challenge was to get fully planar surfaces, as torsion is easily introduced by slight errors in the file preparation.

Robotic Fabrication is quite different to other fabrication methods, as it does not necessarily imply a certain type of fabrication: An industrial robot is a multifunctional, kinematic machine that can be used for many kinds of tasks, from milling to stacking to welding and drilling. The main issue that keeps robots from taking over the fabrication world is their difficult programming. Giving architects the knowledge and tools to program industrial robots is one of our main areas of research. In the exhibition, one piece was partly fabricated by our industrial robot: the *parametric punching* project (Fig. 9) with its parametrically deformed steel panels. Regular cutting patterns were applied to the steel panels with a water jet cutter, locally weakening the panel's structure. Using a custom conical tool mounted on the robot's end-effector, the weakened elements were selectively pushed down by between 0 and 20mm, with an exact value for each push having been extracted from the parametric model. For converting the values into robot-movement code, an in-house developed software was deployed within the parametric design tool, thus circumventing the otherwise tedious workflow from CAD to CAM to robot.

While the planar panel could also have been imprinted using a regular 3 axis CNC machine, we expect to apply this fabrication strategy to curved panels, which would exceed the capabilities of 3 axis machining.

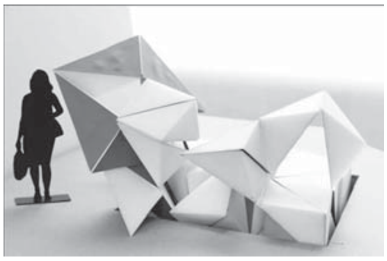

Fig. 8 *Scaled model of the 'Inside Out' cubes hot wirecut*

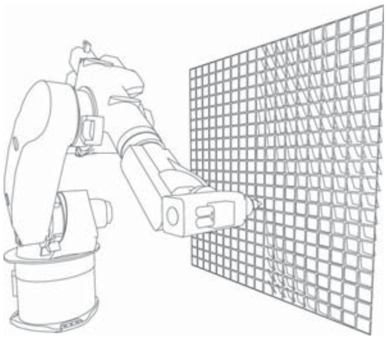

Fig. 9 *Diagram of the robot set up for 'parametric punching'.*

Conclusion

This catalogue documents recent developments in CNC technology and the impact of freeform design as both constraining and liberating future architects and creating forms that have hardly been built. Similar to the question of a good 'design' of freeform architecture, the new generation of architects has to develop a new 'language' in the form of scripting and programming to solve such complex tasks. Being non mathematicians and having been part of the research in Architectural Differential Geometry we are convinced that architects should strive to understand the small geometric entities such as points and vectors that are commonly used for CNC fabrication instead of focusing on mathematically highly complex reengineering arbitrary freeform surface. Both we and our students are lucky to have access to one of the best equipped CNC workshops at architectural faculties in Europe. This helps us create a counterweight to the current overabundance of digital tools and teach both digital fabrication and digital design with exactly the same implicitness and variety.

In the near future, being able to create 2D plans in CAD will not be enough to communicate the design intent or allow the fabrication of freeform structures. Machinic constraints and the relation between simple geometric entities are the keys in breaking down such complex geometries.

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REFERENCES:

Pottmann, Helmut/Brell-Çokcan, Sigrid/Wallner, Johannes: Discrete Surfaces for Architectural Design. in: Chenin, Pierre J./Lyche, Tom and Schumaker, Larry L.: Curves and Surface Design. Avignon 2007, pp. 213–234.

Brell-Çokcan, Sigrid and Pottmann, Helmut: Supporting Structure for Freeform Surfaces in Buildings, Patent No. A1049/2006.

Pottmann, Helmut/Asperl, Andreas/Hofer, Michael and Kilian, Axel: Architectural Geometry. Exton 2007.

Scheurer, Fabian/Stehling, Hanno: Digitaler Holzbau – Komplexe Formen in Holz in: Schwaner, Kurt (Hrsg.): Zukunft Holz. Statusbericht zum aktuellen Stand der Verwendung von Holz und Holzproduktion im Bauwesen und Evaluierung künftiger Entwicklungspotenziale. Hochschule Biberach 2009, pp. 1071–1075.