Robotic Fabrication of Modular Formwork for Non-Standard Concrete Structures

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Abstract. In this work we address the fast and economical realization of complex formwork for concrete with the advantage of industrial robot arm. Under economical realization we mean reduction of production time and material efficiency. The complex form of individual formwork parts can be in our case double curved surface of complex mesh geometry. We propose the fabrication of the formwork by straight or shaped hot wire. We illustrate on several projects different approaches to mould production, where the proposed process demonstrates itself effective. In our approach we deal with the special kinds of modularity and specific symmetry of the formwork

Keywords. Robotic fabrication; formwork; non-standard structures.

INTRODUCTION

Designing free-form has been more possible for architects with the help of rapidly advancing CAD programs. However, the skin, the facade of these building in most cases needs to be produced by using costly formwork techniques whether it’s made from glass, concrete or other material. The problem of these techniques is that for every part of the façade must be created an unique mould. The most common type of formwork is the polystyrene (EPS or XPS) mould which is 3D formed using a CNC milling machine. This technique is very accurate, but it requires time and produces a lot of waste material. On the other hand, the polystyrene can be cut fast and with minimum waste by heated wire, especially when both sides of the cut foam can be used. Therefore, the aim of this project is to explore the mould forming of complex geometries by using a hot wire cutting technique that can potentially diversify and spatially enrich the repetitive aspects of modular systems still pertinent in the production of architecture today. Can we make a use of hot wire cutting technique operated by industrial robotic arm to create a complex mould while minimizing the production time and the waste material? What are the advantages and constrains of using this technique?
HOT WIRE
The hot wire cutting technique uses typically straight heated wire. This constrains the design process into ruled surface geometry, as the ruled surface is formed by continuous sequence of straight line segments. Ruled surfaces have been already used in creating complex architectural forms. One example is the pioneering work of Antoni Gaudi and his Sagrada Familia Cathedral. The interviewing hyperbolic paraboloid geometries of the cathedral’s ceiling vault system are ruled surfaces that can be created by using hot wire. However, the wire can be also shaped to research beyond the ruled surfaces and to explore more geometrical possibilities.

DESIGN TO PRODUCTION
The big challenge was the optimization of the robot data flow from parametric design to a physical model. A Grasshopper component was generated within the project that included inverse kinematics and all the necessary calculation for direct robot programming with an automatic code generation. The basic robot code was supplemented with special strategies depending on individual specific design meant to facilitate the transformation of the desired design to the basic robot code. This approach provided great flexibility in design and real time feedback to the designer due to the robot constrains. The used industrial robotic arm - Robot ABB IR140 constrained the cutting size into 250x250x160mm EPS blocks (Figure 2), that could be to cut into stackable ornamental components, which then composed the negative form-work for the concrete wall design. These constraints necessitated the adaptation of individual design, starting with changes of the initial design, selected tool or EPS tool cutting strategy. Since one of the project aims regards cost-effective use of materials, the first part of the research was started with modular ornamental parametric elements. By varying their parameters and positions it was possible to obtain a huge number of variations of the final design.

WHY ORNAMENT?
Through the history of architecture the role and denotation of ornament was shaped by cultural, intellectual and technical development. The decreasing and increasing use of ornaments in architecture was linked to their use as superficial, mostly two-dimensional and symmetrical elements on the façade. The development from Speiser’s exploration of ornament as a matter of symmetry (Speiser, 1927) to Shubnikov’s analysis of the symmetry method for revealing the invariants of transformation (Shubnikov, Koptsik, 1974) to Semper’s theory of ornament (Fröhlich, 1991) and Loos’s opposition to it (Loos, 1997), to Moussavi’s classification of the ornament based on depth material or effect (Moussavi, 2007) indicates the complexity of the different approaches to the subject-matter of ornamentation.

Particularly new technologies in architecture have a huge influence on the further processing of the ornament as a non-standard element and new systems of production have opened up possibilities for their differentiation and customization. In contemporary architecture we can find examples of contemporary ornaments like laser-cut sheets (Christian Dior Ginza Store, Kumiko Inui), glass tubes (Louis Vuitton Roppongi Hills Store, Jun Aoki), perforated screens (Centre du Monde Arabe, Jean Nouvel), colour-coding effect (Laban Dance Center, Herzog & de Meuron) or silk screened images (Eberswalde Library, Herzog de Meuron, Thomas Ruff).
GEOMETRY OF WALLPAPER SYMMETRY GROUPS

Our geometrical approach is based upon wallpaper symmetry group. This approach enables us to use geometry rules as a design constrains. That leads to the huge design diversity and great potential in the further develop of this topic. From the aspect of mathematics and geometry, all periodic wallpaper ornaments may be classified in 17 groups. Each wallpaper group is characterized by specific plane transformations, which individual elements – the cells of ornaments – must satisfy to be classified in any specific group. The principal geometric property of a 2d cell is that it may be multiplied to cover a plane completely, through various specific transformations of the plane (translation, reflection, glide reflection and rotation). Namely, two congruent figures may be mirrored, using rotation or translation, whereas two symmetrical figures may be duplicated using reflection and glide reflection (reflection followed by translation along the direction of the reflection axis). When it comes to symmetry groups, there are only three different kinds of regular tessellation to be used to cover a plane completely. This type of tessellation is performed with the shapes of parallelepiped, equilateral triangle and regular hexagon. The unit cells of wallpaper ornaments are obtained when these basic geometric shapes are split into identical secondary elements. Figure 3 shows the plan elevations of basic shapes, cells generated from these basic shapes and the types of wallpaper ornament groups they constitute.

FORMWORK

In our project the starting point was the 2d geometry (either without colouring or ornamental motifs) that we developed into 3d module. 3D modules are delineated using space curves between which NURBS geometry is generated. The shaped hot wire allowed us to use any translational or rotational NURBS surface in our design defined with the four border curves of each module.

Periodic tiling

The tiling is based on a symmetric group p4 having two-fold rotation and two four-fold rotation. Geometrically the main shape consists of one polyline mirrored around axe BD. The final form is generated with 90°rotation of base curves through the points A and C (Figure 4). The used 3D form is optimised

Figure 3
a. Basic shapes that may be used to cover a plane; b. Uniform tiling, plane covered with uniform geometry unit cells; c. Unit cells of specific wallpaper groups.

Figure 4
Geometrical rules of p4 ornament as designed inspiration.
and enables cost-efficient use of material and time efficient cutting technique. The three-dimensional form was achieved with the cutting of boundary box with one symmetry plane that divide block into two parts. The second cut was the shape cut of 2d pattern that makes final shape. Generally for this symmetry group the both base curves can have different shape (Figure 5), which open other possibilities and freedom in the design process.

With only two cuts, it is possible to get four elements, two positives and two negative parts of the desired pattern. Negatives are used as formwork for concrete, while the positives can be used as an insulating facade element (Figure 6). This shape also enabled overall between the individual moulds in the four-fold rotational point that has a positive static influence onto whole assembling structure.

Aperiodic tiling have been discovered on quasicrystals and can be generated by projection of higher dimensional grids into two or three dimensions. Theoretically there can be infinite different patterns in one plane without any holes that are able to be continued indefinitely. They are comprised of structures made of few different tiles which are combined in a non repetitive manner. Rotational symmetry makes their non repetitive combination possible as opposed to periodic structures which only have translational symmetry (can be copy and paste next to one another).

An example of aperiodic tiles are the Penrose tiles, discovered by the British mathematician Roger Penrose.

![Figure 5](image1.png)
![Figure 6](image2.png)
![Figure 7](image3.png)
Penrose in the 1970’s prior to the discovery of quasicrystalline structures in 1984. The Penrose tiling can be derived from the projection of five dimensional grids onto a two dimensional plane (N.G. De Bruin, 1981).

The growth of a Penrose tiling is regulated by a finite number of (local) matching rules between tiles (figure 7).

Figure 8
Penrose tiles – different tile patterns derived from basic Penrose tiling rules.

Figure 9
Formwork for Penrose pattern of Figure 8a.

Figure 10
Creating irregularity by shifting the cutting wire.

Figure 11
Formwork for the shifting pattern.
B1 = A2: The B1 and A2 corners can be moved into the Z-direction by equal value.
A1 = C1 = D2 = B2 = D1 = C2: Another Z-value have to be used equally for the other corners.
a1 = b1 = a2 = b2
c1 = d1 = c2 = d2

All of the edges which are coming from the vertex shifted in Z-direction have to be identical. Each of the other corners have to be mirrored around their centre.

This formwork for this tiling can be created by assembly of two different shapes of bricks in the form of rhombuses, one with the corner angles of 72 and 108 degrees and the other with corner angles of 36 and 144 degrees. The height of the corners of those two rhombuses have to be the same in order to form continuous surface, but the shape of the edges can be arbitrary (Figure 8). The example in Figure 9 are cut by only straight hot wire, but a shaped hot wire can be also used.

**Shifted pattern**

Comparing with the previous two projects the aim of this design was to reach the irregularity by multidirectional shifting of the hot wire. In this case only one shaped wire was designed in such a way, that it was possible to cut the foam into two pieces that could be both used for the mould (Figure 11). The used method was based on the translation of the cutting wire in the X-direction and shifting it in the YZ plane (Figure 10). The porosity of the concrete was achieved by second pass of the same wire over chosen locations of one of the formwork’s sides. The size of the porosity was possible to control with the offset distance of the wire during the second cut (Figure 12).

**CONCLUSION, FURTHER RESEARCH**

This research is still work-in-progress. Our first experience shows a great possibilities for the further development of our approach. Our future research focused upon:
• Application of the cutting method for global double curved surfaces.
• Joinery techniques of the modular elements.
• Formwork for high tensile concrete - thin wall surfaces.

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