Spatializing Planar Ornaments

Towards esthetic control in segmenting and building curved surfaces

Milena Stavric[1], *Urs Hirschberg*[2], *Albert Wiltsche*[3]
[1,2,3] *Institute of Architecture and Media, Graz University of Technology, Graz, Austria*
[1,2,3] *http://iam.tugraz.at/*
[1]*stavric@tugraz.at,* [2]*hirschberg@tugraz.at,* [3]*wiltsche@tugraz.at*

Abstract. *This paper gives insight into an ongoing funded research project dealing with architectural geometry and nonstandard fabrication methods. The innovative aspect of the project lies in the way it uses geometric ornamentation as a method to control the construction of double curved free-form surfaces out of planar building elements. After a short outline of the state of the art the paper gives an overview of the project's novel constructive and esthetic approach to the planarization of curved forms, discusses the implications of the approach and presents some preliminary results.*
Keywords. *Architectural Geometry; Nonstandard Structures; Ornament; Mass Customization*

Introduction

Computer aided fabrication has led to a new discussion about the notion of standards in architecture, and the possibility of bringing mass customization methods into the building process (Sass, 2010). But it has also led to a renewed interest in architectural geometry (Pottmann, 2007). As many of the nonstandard buildings currently making use of computer aided fabrication methods are characterized by a formal vocabulary of free forms, double curved surfaces and the like, and as these geometries are notoriously difficult to build efficiently, the new digital fabrication methods require advanced research in geometry. The research project presented in this paper takes on this challenge. The innovative aspect of our work lies in the way we use geometric ornamentation as a method to control the construction of double curved free-form surfaces out of planar building elements. After a short outline of the state of the art we discuss the implications of our novel constructive and esthetic approach to the planarization of curved forms and present some preliminary results.

Nonstandard Geometry

Unconventional geometric shapes and free-form surfaces - also known as nonstandard geometry - have always been something that architects have wanted to design and build. In the history of architecture many of these forms could not be conceived as the design process was restricted by representation media and scale. The development of digital technologies in the last twenty years has led to an unprecedented formal freedom in design and in the representation in virtual space. New CAD software supports the generation and modification of various geometries like solid objects with extrusions, Boolean operations, transformations etc. Furthermore CAD made it possible to work with complex NURBS surfaces using techniques such as splitting, lofting, sweeping etc. This has opened up another large domain. Forms that are generated this way can be very complex, single or double curved or consist of polygonal faces.

Combining non-standard geometry with CAD tools enables a new way of expression and realization of architectural ideas and conceptions. Non-standard geometry has become a fixture in the work of many of the world's foremost star-architects. Given the high degree of attention these geometric extravaganzas garner it seems astonishing, almost paradoxical, that the field of architecture as a whole is not investigating such geometries more thoroughly. In this age of digital-virtual architecture where complex non-standard architectural forms are possible there really is only a small number of architecture firms that have acquired the know-how to make use of this enormous potential which makes non-standard architecture more buildable (Kolarević, 2003,2008; Hirschberg, 2009).

Typically there is a disconnect - both in terms of software used as well as people in charge - between the design of the free-form architecture and the conception of the construction method which then makes these free forms buildable (Vrachliotis and Scheurer, 2009). The main reason for this disconnect is not so much a lack of interest in construction on the part of the designing architects as it is a lack of tools that would support a more integrated approach. The software that is used in creating the free-form geometries typically doesn't provide much support for dealing with the complex constraints of the construction process. The tools used as part of the construction process on the other hand, are at this point very complex to use and only provide basic support for most nonstandard cases. More often than not coming up with a strategy to go from the design to the digital fabrication involves writing one-of solutions such as scripts and geometry-translators. As few architects have these skills (although this might change if more emphasis is laid on architectural geometry in architectural education in the future) it is only natural that specialists tend to take over at this point. But this situation is hardly satisfying. It creates a high amount of redundancy (digital models typically have to be rebuilt from scratch by the specialists) and a lack of control over the construction process on the part of the designers.

The project we are presenting in this paper does not attempt to completely eliminate this division of labor. We think that the need for specialists is probably here to stay. Nevertheless it aims to extend the reach of the designing architect into the construction and fabrication process and thus to move towards more efficiency and more integration in professional practice.

Strategies for building curved forms

There are different ways how the construction of curved shapes can be approached. As the ideal, mathematically perfect shape is something that can only be approximated under real-world conditions, choosing a construction strategy also means choosing a way to keep errors and imprecisions within bounds. If the construction-principle is well chosen, it will underscore, rather than compromise the design-intent. Therefore, which strategy is appropriate largely depends on the design intent, but also on very pragmatic issues such as efficiency and cost.

There are prominent examples of free-form buildings by renowned architects, where every effort was made to arrive at completely smooth curved surfaces. These remarkable buildings usually involve the construction out of planar elements, which are then bent to arrive at the curved form. See for example the titanium panels on the Bilbao Guggenheim by FOGA or the concrete 'sixth façade' of the Rolex learning center at EPFL by SANAA8 [Fig. 1].

The construction strategy we are presenting here does not follow these examples as our approach involves no bending. Instead, it approximates a curved shape by building it out of truly planar elements. Thus, the resulting shape is really no longer a smooth, curved, but a faceted, polygonal shape.

Figure 1
Rolex Learning Center by SANAA. Smooth poured concrete surface made using bent planar elements

Obviously this is a strategy that will not be acceptable in all cases. On the other hand this approach has potential advantages in terms of efficiency and cost: many standard building materials come in flat panels that can be cut to size. Therefore this basic construction principle could be applied to a wide variety of materials. Our approach to discretization is based on the latest results and the ongoing research about discrete freeform structures within the new research field "Architectural Geometry" (Pottmann, 2007). Due to its economic and constructive advantages we believe our approach has the potential to become a common method to build such forms. As part of the project we are specifically investigating industrially manufactured Cross Laminated Timber (CLT), a composite wood material.

It should be pointed out that, while efficiency and cost are among the main advantages of our approach, it is by no means trivial. At first it may seem a bit of a letdown to construct curved surfaces as polygonal surfaces. It is only on closer inspection that both the esthetic potential and the geometric complexity of this approach emerge. We will deal with both of these aspects in the following sections.

Geometric complexity: Discretization problem of curved forms

The purpose of our work is to explore a new way how nonstandard architecture can be built material- and cost-efficiently by using standard building elements with state-of-the-art building processes. We concentrate on discrete forms and surfaces, approximating complex curved shapes with flat panels. This discrete shaping however is not based on the commonly used triangulation resulting in three-sided panels [Fig. 2], but rather on patterns, proportions and symmetries of classical ornaments typically consisting of polygonal faces with more than three sides (Shubnikov and Koptsik, 1974).

One advantage of using these ornamental patterns lies in the fact that the jointing of the panels during construction becomes easier, the fewer edges meet in one point. Having just three panels meet in one point is ideal. As soon as four panels meet, offset problems occur due to the thickness of the panels. We handle this problem by using mainly knots with vertex configuration (k, l, m) with k,l,m Î {3,4,5,6,7,8}. This means that only three panels meet at most vertices [Fig. 3]. If four panels meet at one vertex we handle this by using conical meshes in the surrounding area (Pottmann, 2007). Thus, using quads, pentagons, hexagons etc. rather than triangles simplifies matters related to construction. But on the other hand it makes the segmentation process much more difficult.

While segmenting a curved surface into triangular patches is mathematically trivial, doing the same for polygonal faces with four or more edges is not. It is simple to map any polygonal pattern onto a curved surface using the u- and v- parameter lines as an underlying grid [Fig. 4, left]. But as this mapping automatically turns all lines of this pattern into curves, and only three points will always be guaranteed to lie on one common plane, finding a matching polygonal structure out of planar elements in which all sides are perfectly aligned is a very tricky optimization problem for which there is no clearly defined solution. We have developed a novel approach to this problem, which we have described in Stavric and Wiltsche (2010). It allows us to come up

Figure 2
Triangulation - Milano Fair by Massimiliano Fuksas Architects

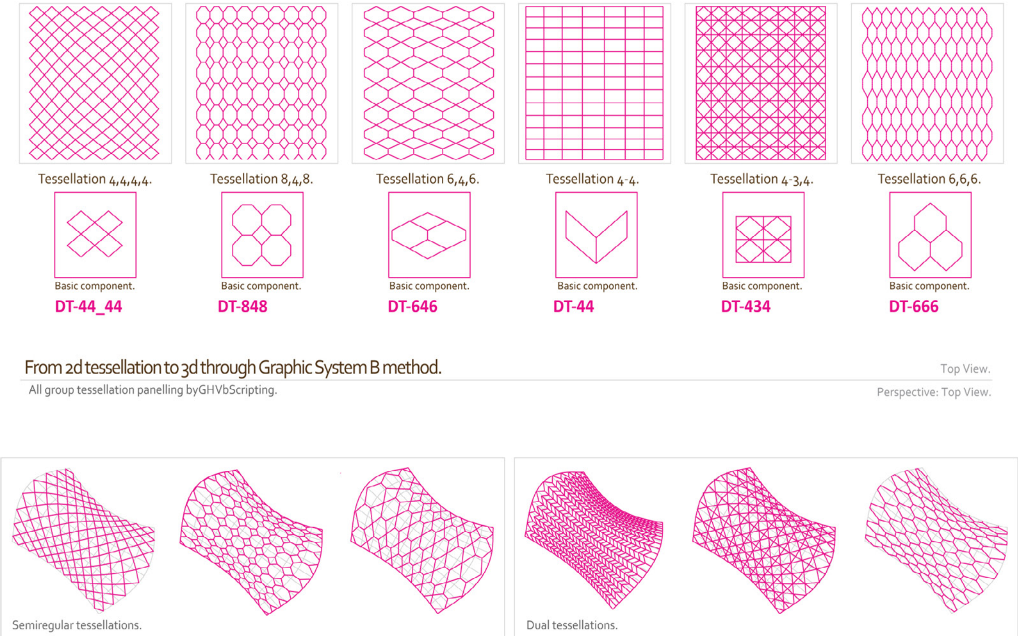

Figure 3
Choice of different ornamental topologies: Patterns DT-848 and DT-666 have advantages over the others shown as they include only points where no more than three panels meet, thus eliminating the offset problem.

with a solution for regular cases. Note that the proportions of the pattern are somewhat altered in the process, but the basic topology is preserved [Fig. 4, right].

This step from [Fig. 4, left] to [Fig. 4, right] is what we refer to as the spatializing of ornament. Whereas the pattern on the left is only mapped onto the surface and remains twodimensional in nature, in the right version it has become a spatial structure. In the spatializing process each pattern is turned into planar tangent face. All these tangent planes intersect and build a spatial ornamental pattern-mesh.

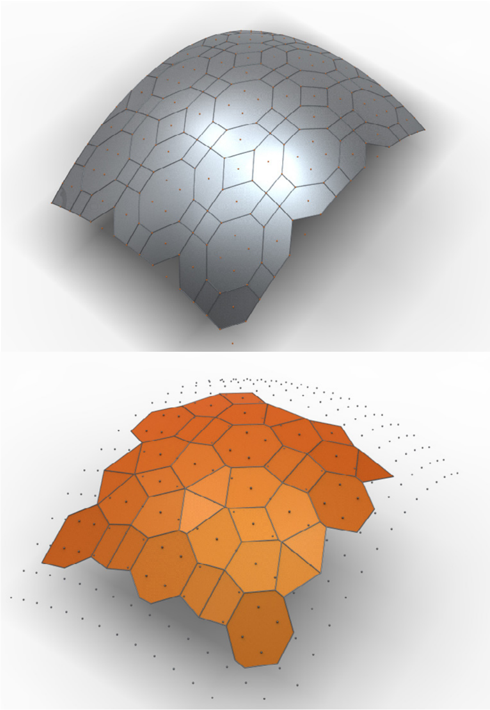

Figure 4
Spatializing ornament: Non-planar (left) and planar (right) ornament pattern on a double curved surface.

Esthetic potential: Spatial ornament and construction

The discretization of curved surfaces using ornamental patterns is a geometric challenge. It is worthwhile investigating it, not only because of the mentioned practical issues such as efficiency and cost, it also opens up a new esthetic potential. While a polygonal shape will never be a smooth curved surface, it can nevertheless come pretty close. And along the way it opens up the topic of the segmentation, which can have an esthetic value in itself. In fact, the premise of our project is to focus on this act of segmentation. Rather than leaving it up to random mathematical algorithms, our goal is to give the designer control over the segmentation process and its ornamental qualities.

Art, history, architecture, and mathematics have different explanations and approaches to the term "Ornament". Only a mathematical approach with its rules and symmetries gives us the required precise control of the ornamental pattern. We use the mathematical systematic of symmetries (Shubnikov and Koptsik, 1974) in order to generate an initial set of patterns the user can choose from. Then we map them onto a chosen freeform surface using the uv-parameter grid. This leads to non-planar patterns, which are then spatialized as described above [Fig. 4].

Esthetic control is achieved through parametric fine-tuning of the ornament mapping, affecting the topology as well as the proportions. The generation of the initial 2D-pattern is based on a choice of basic ornamental topologies. The pattern can then be further manipulated until the final result is determined by changing each tangent plane using the corresponding u and v parameters on the surface. As can be seen in Fig. 4, the form-driven or willful altering of proportions and densities of the ornamental patterns across a curved surface can have striking esthetic effects. It should be noted that the patterns in Fig. 5 are mapped and not yet spatialized. As can be seen in Fig. 4 and Fig. 7, the process of spatialization leads to some changes in the proportions of the pattern mesh.

Sometimes, depending on the intended pattern and allowable tolerances it is impossible to find a solution for the proposed pattern. We envision a

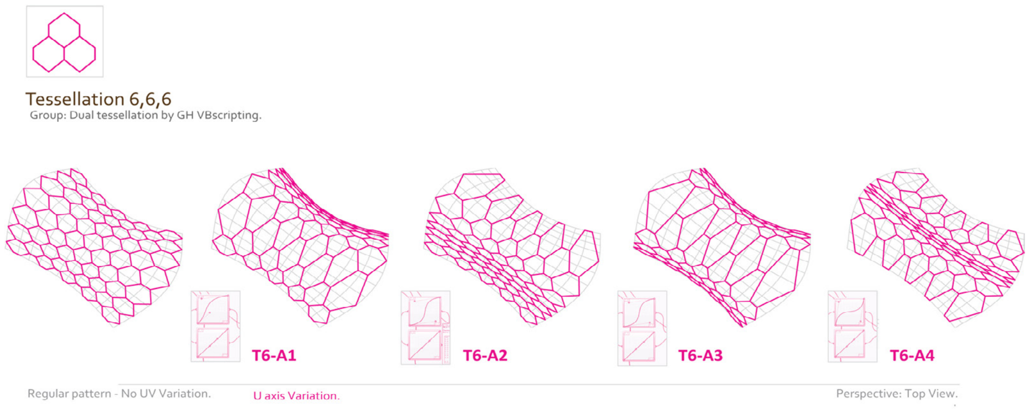

Figure 5
Influence of proportional variations on an ornamental tessellation pattern

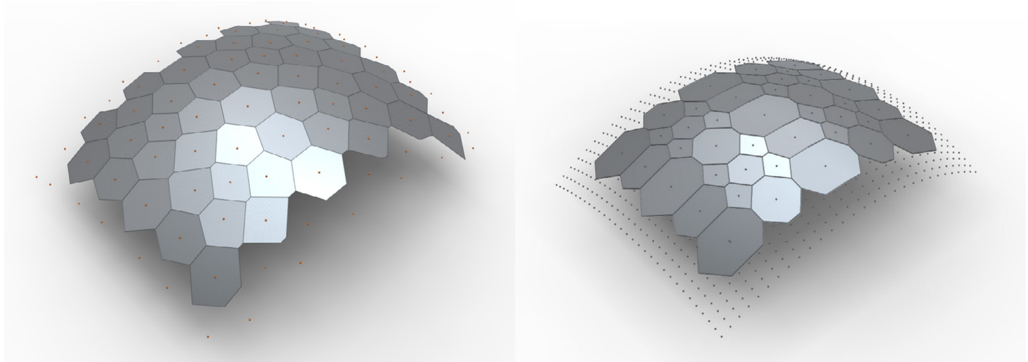

Figure 6
The first spatial planarization version of an ornament (left) and the desired one - after changing the location of the tangent planes (right).

system which lets the user easily control the projected patterns and which provides feedback about the resulting spatialized pattern-meshes. To optimize the structure according to different user-driven criteria, such as proportion, proximity to curvature, etc. we are developing a parametric system in combination with genetic algorithms. The system will allow the user to easily refine the planarization to the desired result as seen in Fig. 5 and Fig. 6.

Built Prototype out of wood panels

Six months into a project that will run for three years we can only present preliminary results. To properly convey the overall approach we are taking it is important to point out that besides geometric und user interface issues another main focus of the project lies in the actual constructing and building. At the final stage of the project a self supporting structure consisting of standard building elements will be built using the approach discussed before. For this prototypical structure we decided to use industrial manufactured Cross Laminated Timber (CLT) boards with a size of 100 x 200 cm for cost efficiency. A small number of customized hybrid boards (laboratory manufactured) will be used for additional load tests and tolerance checks. The type of wood for the industrial boards will be spruce, for the customized boards we will use ash tree for its excellent material properties. The prototype will be a closed single-leaf structure which can be easily assembled on site.

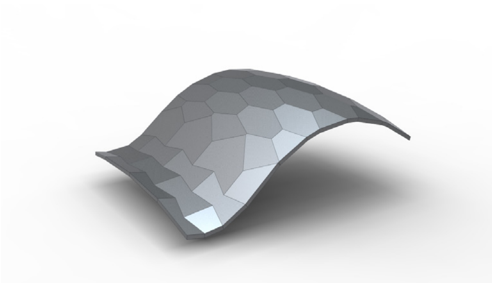

Figure 7
Depending on the Gaussian curvature, the hexagonal pattern can switch to a butterfly shape during spatial planarization

Conclusion

This paper has presented a novel approach to the segmentation of free-form surfaces in architecture. Using ornamental patterns rather than triangulation in the discretization of double curved surfaces, the approach is geometrically challenging but promises simplified and cost-efficient assembly as well as new esthetic qualities. We see the spatialized ornamental patterns as a contribution to the ongoing debate about the resurgence of ornament in architecture. The ornamental topologies we use in order to make free-form surfaces easily buildable are interesting because they are not merely applied patterns, but have a structural and spatial meaning.

The tool we are developing in this research project promises to let these patterns be determined by the decisions of the designer as well as the mathematical conditions of the curvature - in a process that mixes design-intent and geometric optimization. We feel that this partnership of designer and machine and the ambition to use high-tech planning and fabrication in order to enable low-tech assembly are a promising strategy. While this is a preliminary report on an ongoing project and we have yet to deliver on these promises, we feel that this is also the general direction in which the field of digital fabrication in architecture should be moving in the coming years.

Acknowledgements

This work is supported by the Austrian Science Fund (FWF) under the grant L695.

References

Hirschberg, U et al. (eds.) 2009, 'Nonstandard Structures', *GAM - Graz Architecture Magazine 06*, Springer,Wien NewYork.

Kolarević, B (ed.) 2003, *Architecture in the Digital Age: Design and Manufacturing*, Spon Press, London.

Kolarević, B and Klinger, K (ed.) 2008, 'Manufacturing Material effects', *Rethinking Design and Making in Architecture*, Routledge, New York.

Pottmann, H, Asperl, A, Hofer, M, Killian, A 2007, *Architectural Geometry*, Bentley Institute Press, Exton, Pennsylvania.

Sass, L 2010, 'The Next Revolution: Digital Building Kits', *New Frontiers: Proceedings of the 15th CAADRIA Conference*, Hongkong, pp. 545 – 553.

Shubnikov, AV and Koptsik, VA 1974, *Symmetry in Science and Art*, Plenum, New York.

Stavric, M and Wiltsche, A 2010, 'Geometric Methods of Spatializing Ornaments', *Advances in Architectural Geometry*, Vienna, submitted.

Vrachliotis, G and Scheurer, F 2009: 'What is being asked for are Cathedrals for free - A look behind the Scenes of Digital Building Construction' *in GAM - Graz Architecture Magazine,* 06: 2009, Nonstandard Structures, Springer, Wien NewYork, pp. 206 – 215.