Study of Panelization Techniques to Inform Freeform Architecture

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Keywords

Abstract

The authors give a qualitative analysis of past and present techniques for the panelization of freeform architecture. These techniques are compared by economy, constructability, and adherence to the original design intent. From this analysis the authors conclude that the industry is currently transitioning from a state of "Can we build this?", to a state of "Should we build this?". A discussion of future trends and open problems of panelization theory is given.

Introduction

Over the past two decades, the architecture and design industry has undergone a digital revolution. CAD, 3D modeling, and script driven design programs are commonly used in most major architecture offices around the world. Modeling technology is now so advanced that it is possible to produce extremely complex geometrical forms from minimal design input. As a consequence, the prominence of freeform geometry in the built environment has grown rapidly during this time. Although there is no doubt that this new found freedom has given rise to some incredible and beautiful forms, it has also widened the gap between the original design intent of a project and what can reasonably be constructed. This tension is especially apparent in the structural glass industry, since it has been the medium of choice in a wide variety of projects involving freeform geometry.

In order to investigate this situation, we have created a study project environment in which we bring a freeform surface from initial sketch to fully coherent, although not always feasible, design solution in a number of different ways. The techniques we have chosen progress from past to present and include triangulation, rationalization by primitive objects and rotational surfaces, discretization via conjugate curve networks, and developable strip modeling. Each of the resulting design solutions is then evaluated on node simplicity, structural transparency, adherence to original design intent, and material wastage.

Figure 1:

Design intent for a free-form surface
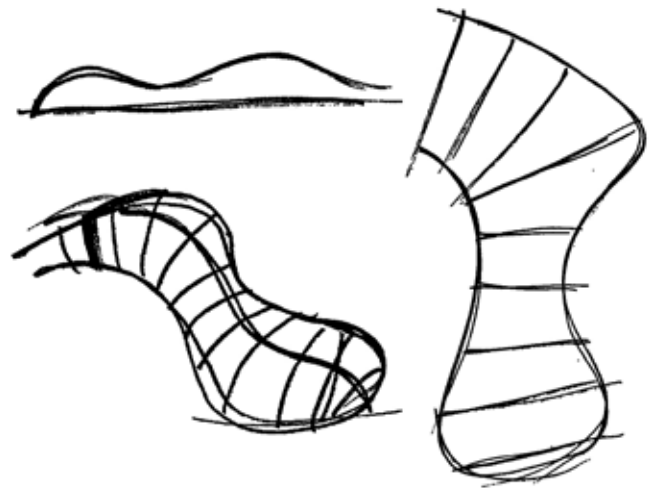
From this investigation we conclude that presently the industry is at crucial point. Until now, we have been trying to answer the question: Can we build this? It is our belief that in the context of glass panelization of freeform geometry, this question has been answered in the affirmative. We can begin to investigate the question: Should we build this? A question that is especially important given the current financial trends.

Objectives

All architecture projects begin with an initial sketch or model illustrating the main design concept. We assume that the form is presented as a smooth surface modeled with a commercially available modeling package, in our case, Rhinoceros3D. Our task is to produce a design solution that panels the surface in such a way that node simplicity, structural transparency, adherence to original design intent, and material wastage are optimally balanced. We will use the term "optimal" in both a qualitative and quantitative way, and will clearly indicate which one is meant. In addition, our design solution will be given as layout with which one could design the physical nodes, and although we will give an example of how this might be done, we will not complete the design in general.

The panelization techniques will be given a number between 1 and 5 in each of the mentioned categories. We use the convention that 1 implies poor performance and 5 implies excellent performance. Node simplicity will be evaluated on the ease of connection and the torsion of the structural elements at each node. Structural transparency will be evaluated on the complexity of the details necessary to finish the design and number of edges that meet at a typical node. Adherence to original design intent will be the amount that the panelization scheme deviates from the original surface. Material wastage is the percentage of the bounding box that a standard panel occupies.

Initial Surface

Although freeform geometry does not have an official definition, it can generally be recognized by its smooth, flowing lines, unique and varying shape, and lack of inherent symmetries. Our study surface, although not wildly bizarre, is a freeform surface, and is complex enough to make the panelization process difficult (Figure 1).

Triangulation

The first panelization technique we consider is that of triangulation. Approximating a smooth surface with triangular elements is the oldest and still most popular way of panelization (Figure 2). It is particularly well suited for panelization with glass, since it is always possible to construct a flat

element through three points. However, a discretization into triangular elements has a number of serious drawbacks. Such schemes will have the highest panel count of any scheme, resulting in the highest number of overall cuts. A triangular scheme also means that six edges meet at a typical node, which implies high node complexity and low structural transparency.

Despite their flexibility, there are certain geometrical conditions that have considerable influence on the appearance of triangular meshes. These conditions are well known in the world of differential geometry, and relate to the curvature of the underlying surface. Thus, there is an inseparable link between the panelization scheme and the geometry of the smooth surface. In order to fully understand and control this link, we must introduce some new terminology.

A mesh is a set of points that are connected in some predetermined way. Pairs of connected vertices are called edges and groups of three or more connected vertices are called the faces of the mesh. Knowing which vertices are contained in a given edge or face is called knowing the combinatorics of a mesh. Meshes are the discrete analogue of smooth surfaces and will give the basis for the panelization scheme. However, the geometrical theory behind meshes is significantly different from that of smooth surfaces. This difference is often the cause of many of the issues that arise when paneling freeform surfaces. For instance, given two smooth surfaces, the distance between them is measured by the distance between corresponding points. Given two meshes, there are three different ways of measuring the distance between them: the distance between vertices, edges, and faces (Figure 3) ([3]).

In fact, a fundamental result of panelization theory is that the meshes most suited for structural glass panels are those for which a second mesh exists that can maintain a constant distance from the original one in at least one of the three ways ([2]). Such meshes are called offset meshes and are currently being developed by members of the Geometric Modeling and Industrial Geometry group at TU Vienna, and the Discrete Differential Geometry and Kinematics in Architectural Design group at TU Berlin.

Planar Quadrilateral Meshes: Primitive Approximation

A planar quadrilateral (PQ) mesh is a mesh whose faces consist of four, coplanar, vertices ([2]). Planar quadrilaterals fit their bounding box more efficiently than triangles and reduce node complexity. It is clear that PQ meshes have many desirable properties, but since four random points almost never lie on a plane, they are quite difficult to apply to an arbitrary surface.

Figure 2:

A triangulation of the surface with structural elements
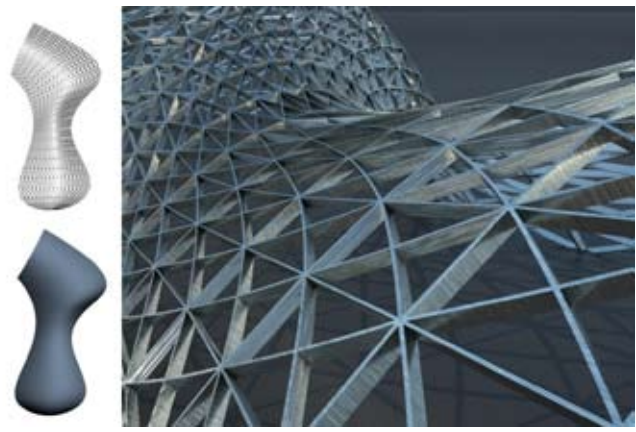
Design Solution 1	Node Simplicity	Structural Transparency	Design Intent	Material Efficiency
Triangulated Surface	1	1	3.5	2.5

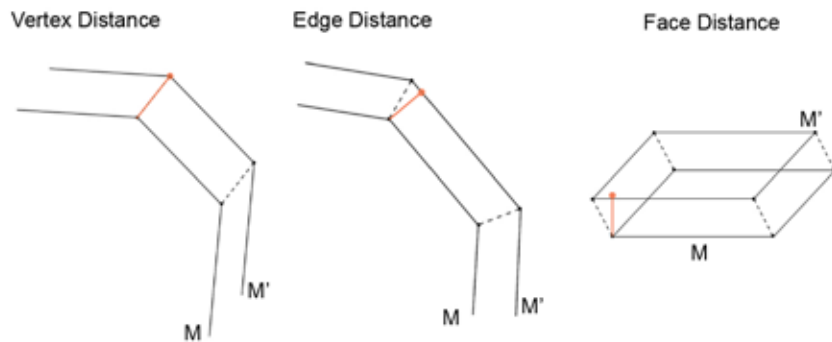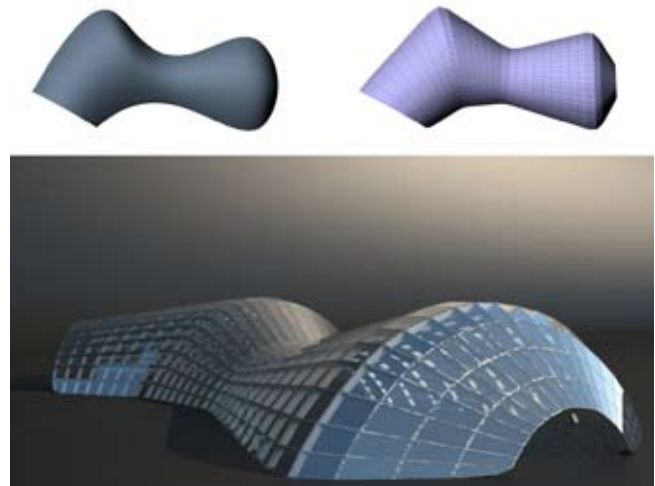Table 1: Our analysis of a panelization scheme based on triangles

Figure 3: The three different ways of measure the distance between meshes

Figure 4:

Approximation by cone segments

Design Solution 2	Node Simplicity	Structural Transparency	Design Intent	Material Efficiency
Primitive Approximation	1.5	3	2	3.5

Table 2: Our results for panelization by primitive approximation

If, however, the surface is not arbitrary, but part of a special class of surfaces that is already well understood, then creating PQ meshes is straight forward. Figure 4 shows our approximation of the original surface by primitive objects, in this case, cone segments.

Planar Quadrilateral Meshes: Fitted Rotational Surfaces

Translational and rotational surfaces are excellent examples of surface that can approximate a freeform surface while maintaining a standard underlying structure ([1]). Although there are some very sophisticated techniques for 'fitting' translational surfaces to freeform ones, unless the original surface is designed with this process in mind, most of the original intent will be lost (Figure 5).

Planar Quadrilateral Meshes: Principal Curvature Meshes

In the years 2005-2007, techniques for adapting PQ meshes to freeform surfaces were developed ([2], [3]). These techniques require the underlying surface to be parameterized along certain classes of curve networks, called conjugate curve networks. If we take the intersection points of well spaced conjugate curve network as vertices of our mesh, then the resulting panels will be close to flat. Using the optimization procedure proposed in ([2]), we can minimally perturb the vertices so that the panels are completely flat (Figure 6).

If, in addition, we use the network of principal curvature lines as the conjugate curve network, then the result mesh will be a face offset mesh ([2]). This means that each of the faces can be offset a constant distance along its normal direction. Adjacent planes will intersect in a point, and these points will be the vertices of a new face offset mesh at a constant distance from the original one, resulting in torsion free and prismatic structural elements ([3]). Face offset meshes are ideal for the multilayer nature of a structural glass panel (Figure 7).

Developable Strip Model:

As a further refinement of the planar quadrilateral model, developable surfaces can be used to interpolate between adjacent lines of one family of parameter lines ([4]). Panels cut out of a developable surface will be bent only in one direction, which is more costly than flat panels, but not nearly as costly as doubly curved panels. It is also possible to use a small number of oversized moulds to reduce fabrication costs ([4]).

There is no question that conical meshes solve most of the traditional problems associated with paneling smooth surfaces with glass panels. However, they also raise a number of new issues. For instance, since face offset meshes depend heavily on the principal curvature lines of the
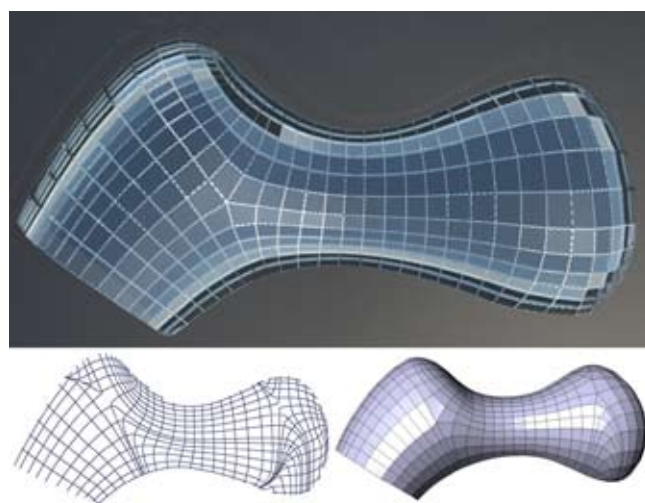
Figure 5:

A rotational surface with PQ panels compared with original surface

Design Solution 3	Node Simplicity	Structural Transparency	Design Intent	Material Efficiency
Fitted Rotational Surface	4	3.5	2	3.5

Table 3: Our results for panelization by rotational surfaces

Figure 6:

A face offset mesh with structure and the underlying curve network

Design Solution 4	Node Simplicity	Structural Transparency	Design Intent	Material Efficiency
Principal Curvature Mesh	4	4	4	3.5

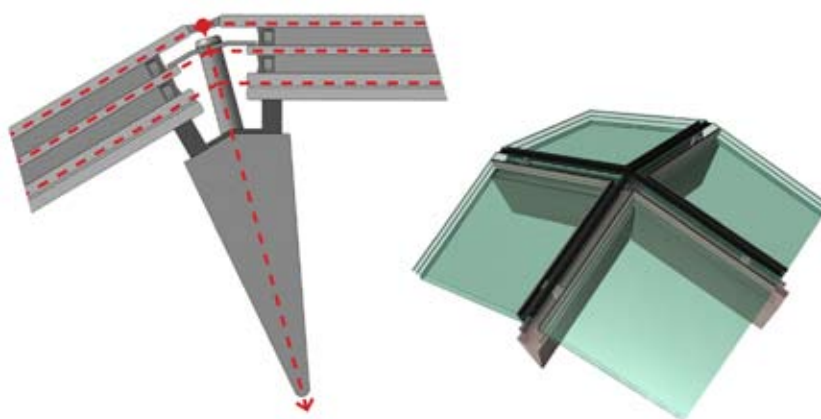Table 4: Our results for panelization by principal curvature lines

Figure 7: Multilayer design of structural glass panel

surface, some surfaces will produce a face offset mesh that is not suitable for construction. Singularities and impossible panel sizes can occur on even very simply surfaces. This is a result of the surface having complicated differential geometry characteristics, despite being simple in appearance.
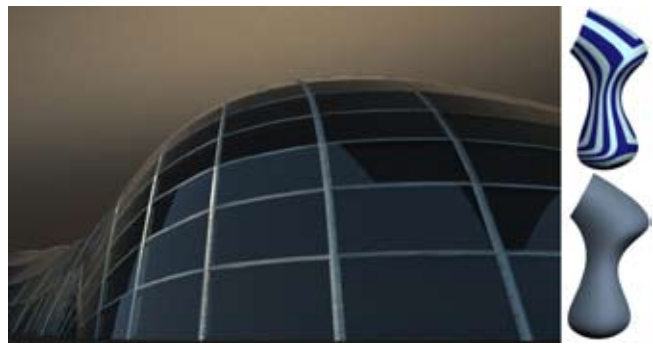
Results

We summarize the results of our qualitative survey of different panelization techniques in the following matrix (Table 6). The results show that the principal curvature mesh provides a constructible panelization scheme for our study surface.

Standardization

The study of different panelization techniques shows how powerful standardization of certain elements in the construction of freeform geometry can be. Standardization can be interpreted as avoiding specialized units, such as doubly curve panels, or it can be interpreted as the repetition of certain elements throughout the project. A particularly powerful example of this would be to standardize the beam depth for a give freeform shape. Such meshes are called edge offset meshes and can be applied to certain kinds of shapes. It is still unknown if they can be applied to an arbitrary surface ([3]). Standardization can also be achieved by having some degree of repeatability in the types of panels that are used. This would achieve economies of scale and facilitate fabrication. However, in order to be effective, there has to be a very small number of different kinds of panels relative to the overall panel count. This ratio can generally not be achieved with a basic error correcting detail in the structural support. For flat surfaces the theory of periodic and aperiodic tiling is well understood, but for smooth surfaces it is not so well documented. Figures 9 - 11 show some alternate paneling schemes that explore possible avenues of investigation.

Figure 8:

Approximation with developable strips

Design Solution 5	Node Simplicity	Structural Transparency	Design Intent	Material Efficiency
Developable Strip Model	3	4	4.5	2.5

Table 5: Our results for panelization by developable strips

Design Solution Comparison	Node Simplicity	Structural Transparency	Design Intent	Material Efficiency
Triangulated Surface	1	1	3.5	2.5
Primitive Approximation	1.5	3	2	3.5
Fitted Rotational Surface	4	3.5	2	3.5
Principal Curvature Mesh	4	4	4	3.5
Developable Strip Model	3	4	4.5	2.5

Table 6: The table of results

Figure 10: A panelization scheme that maximizes sun exposure at a given time
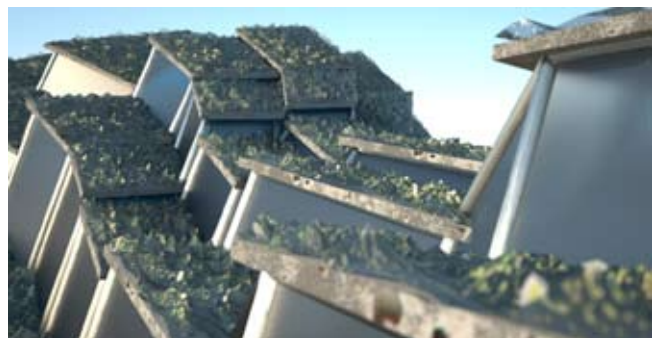

Figure 9: Alternate panelization schemes

Figure 11: Application of directed panels

Conclusion

The results of our study show that the panelization scheme given by the theory of offset meshes performs best in balancing structural transparency, node simplicity, design intent, and material economy. However, the true impact of offset meshes goes deeper than that. We can now view freeform geometry as we would any simpler surface. Offset meshes provide a benchmark against which we can compare an array of panelization techniques. Schemes that further simplify and rationalize panel layout can be viewed as reducing costs, and schemes that add complexity to the panel layout can be viewed as added premiums. We believe that incorporating a detailed study of different panelization techniques into the dialogue between architect, engineer, and contractor will dramatically increase our ability to responsibly and economically realize the visions of the world's most dynamic designers.

References

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