Digital Architectonics :

A Framework for Façade Optimisation

by

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Introduction

The Digital Architectonics research group of the Department of Architecture and Civil Engineering at the University of Bath, UK, in collaboration with sponsors Informatix Inc., is developing new techniques for creating efficient, optimised façades for complex doubly-curved buildings.

A number of approaches to the geometric modelling of complex shaped facades are traditionally adopted, from rationalisation using translation shells or geometric-primitives such as sheared-cones and torus patches, to modelling in a free-form manner using NURB surfaces. Whilst rationalisation simplifies the geometry for construction, with modern computer-controlled manufacturing techniques, repetition and flat-panelisation are becoming less important as drivers for façade design. On the other hand, NURB surfaces can be freely manipulated, but are often viewed as a little too free, in that they have many degrees of freedom and are computationally demanding so it is difficult to use them in any structured way for computer-controlled optimisation.

The term Digital Architectonics refers to the application of digital technology to the field of architecture. The underlying premise of the research group's work has two aspects. Firstly to explore the benefits that a particular surface modelling technique known as Subdivision Surfaces can bring to the field. And secondly, to create software incorporating these techniques into an integrated analysis and optimisation framework, such that information into the consequences of design decisions in terms of both environmental and structural performance can be used early design process to direct the design to a more holistic and efficient solution.

A basic introduction to subdivision surface modelling follows, and in particular the specific properties of subdivision surfaces that lend themselves especially well to use in the design of complex geometry façades are highlighted. Their application to the optimisation of façades for environmental and structural performance is then discussed through reference to case studies, and concludes with an outline of the future research direction of the group.

Subdivision Surface Modelling

Subdivision surfaces have been developed mainly for use in the computer gaming and animation industries, where large models need to be quickly created, rendered and analysed. From a coarse underlying polygonal mesh, a recursive subdivision algorithm is applied, whereby each face of the mesh is subdivided and the coordinates of the new finer mesh are calculated as weighted averages of the surrounding vertices, as shown on Figure 1.

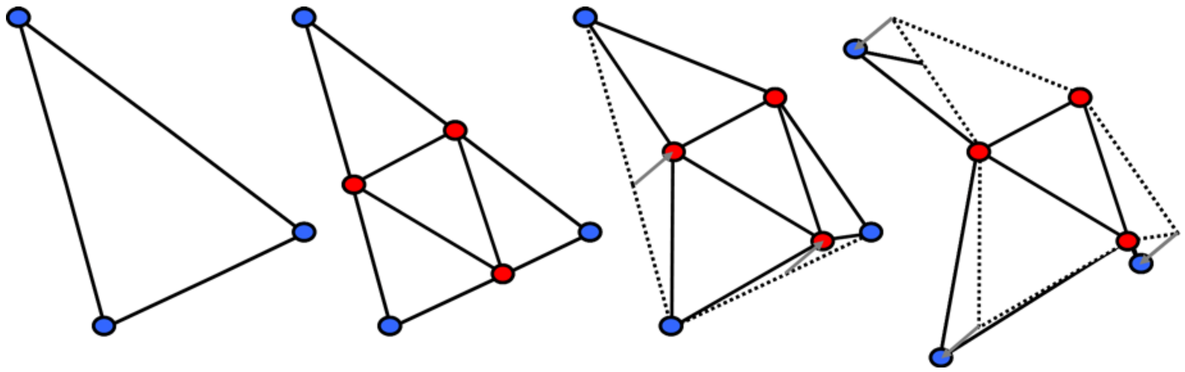

Figure 1 Topological subdivision of a mesh face (left) followed by coordinate smoothing (right)

This subdivision process can be continued indefinitely, with the mesh becoming finer and the geometry converging onto a limit surface, as shown on Figure 2. A number of different subdivision schemes are available, some for triangular meshes, others for quadrilateral or polygonal meshes. The exact details of these smoothing algorithms are carefully calculated to give a limit surface with mathematically continuous curvature, resulting in an aesthetically pleasing limit surface.

Figure 2 Tetrahedral control mesh (left), converging on its limit surface (right), after subsequent subdivision operations.

The hypothesis of this research is that these limit surfaces have many useful properties which make them suitable to represent the façades of complex-geometry buildings.

Firstly, unlike NURB surfaces, since the subdivision surface is defined using an initial control mesh, a parameterisation of the underlying surface is not needed. This is particularly useful when the topology of the surface is complex and modelling in NURBS would require seams and joints (i.e. there are discontinuities in the UV-parameterisation of patches).

More importantly, subdivision surfaces do not need to be subdivided infinitely many times in order to generate the limit surface. Mathematical operations are available to calculate the eventual positions of the mesh vertices directly. So in practice the original control-mesh is divided a few times until a required level of detail is achieved, and then the position of the limit-surface at these points is directly evaluated. This provides a multi-resolution framework whereby different areas of the structure can be defined to different levels of detail as required. This variable level of detail is hugely important when computationally demanding analysis of the façade's behaviour is required. The surface can be subdivided down to a required size and an analysis performed on the divided mesh to give results of any desired resolution, thus giving a flexible balance between performance and accuracy.

By ensuring the surface is smooth, exact control over the position of the surface is devolved to the smoothing algorithm. Whilst smooth surfaces are often desirable, it is imperative for architectural applications that control over the boundary of a surface is possible. For example, the left hand side of Figure 3 shows an attempt at using a triangular subdivision mesh to generate a roof to cover a rectangular atrium similar to that of the British Museum in London. Although very easy to generate, the algorithm attempts to smooth the corners of the roof, leaving them uncovered. Obviously this is not suitable for modelling such an architectural design, and so a process of constraining the surface to a boundary has been implemented. The mesh vertices have their ideal (smooth) position calculated as usual, but then are snapped back to their respective boundaries, as shown in the right hand side of Figure 3. Whilst this does mean that the smoothness of the form is compromised near the boundary, this effect is only local to the boundary and the distorted area shrinks as further subdivisions are made. In this way, specific boundary shapes can be imposed where needed, and the rest of the façade generated with the smoothing algorithm as normal.

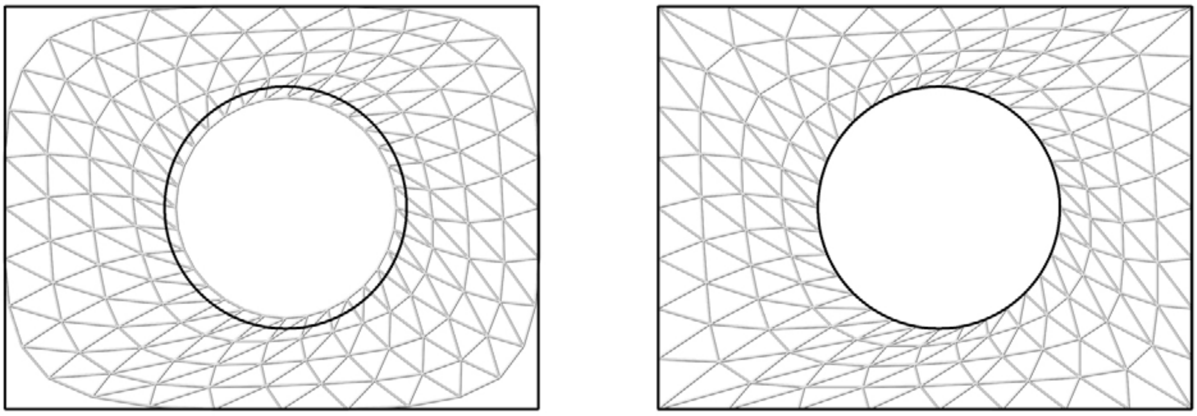

Figure 3 Plan view of a rectangular atrium roof using standard subdivision (left) and constrained subdivision (right).

Additional attributes can also be assigned to each vertex and smoothed in the same way as the coordinates. In the computer graphics arena this is often used to distribute colour, surface-normal or texture-coordinate information across the subdivided mesh in a smoothly changing manner. If the limit-surface is to represent a façade, these additional attributes could also be used to represent properties such as surface reflectance, ventilation level or louver shading-angle. For example, Figure 4 shows a façade similar to that of the Lansdowne Road Stadium in Dublin where the level of red colour indicates the angle of opening of a rain-screen louver system. In successive subdivisions, a weighted average of the colour (=angle) is inherited by the vertices in the same way that they inherit weighted averages of the coordinates. This results in the opening-angle being blended throughout the façade in a smooth transition between open and closed.

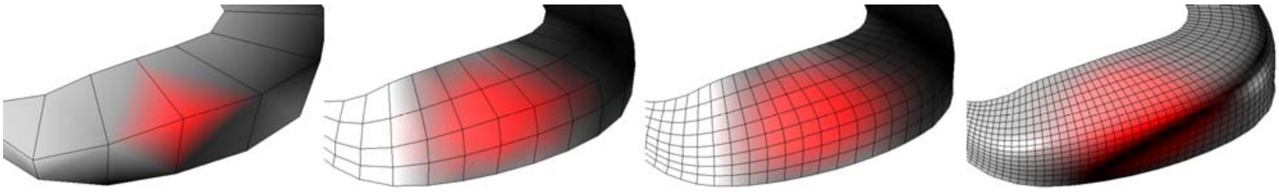

Figure 4 Façade elevation with colour to represent louver angle.

Optimisation for Environmental Performance

The recursive nature of subdivision surfaces allows fast generation of multiple levels of detail of any given surface from the coarse control mesh. This provides a framework for efficient analysis of the environmental performance of a proposed façade, and allows feedback from such an analysis to inform the surface generation through a process of iterative optimisation.

This method was used to optimise the design for the new Aarhus Botanical Garden Hothouse in Denmark by C. F. Møller Architects and Søren Jensen Engineers. A dome-like structure was required to house tropical plants from the botanical garden's collection (Figure 5). Environmental performance was an important driver in the design process, since the internal temperature and humidity needed to be carefully controlled to maintain healthy plant growth. Since the plants required tropical conditions, but the city's climate is northern-European, a significant amount of energy would be required to heat the building. Maximising solar gain would therefore reduce energy requirements, so long as over-heating (and therefore the need to provide mechanical cooling) could be avoided. Whilst these two goals seem contradictory, the northern location of the site meant that the significant difference in winter and summer sun-angle could be capitalised upon.

Figure 5 Proposed new hothouse building for Aarhus Botanical Garden.

Firstly, a dome geometry was quickly generated using seven control points, six fixed in a hexagonal base, with a seventh apex control point above, as shown in Figure 6. Different design options for the dome could then be instantly created simply by moving the single apex vertex. In this way, the subdivision surface framework has reduced the number of degrees of freedom to simply the three coordinates of the apex.

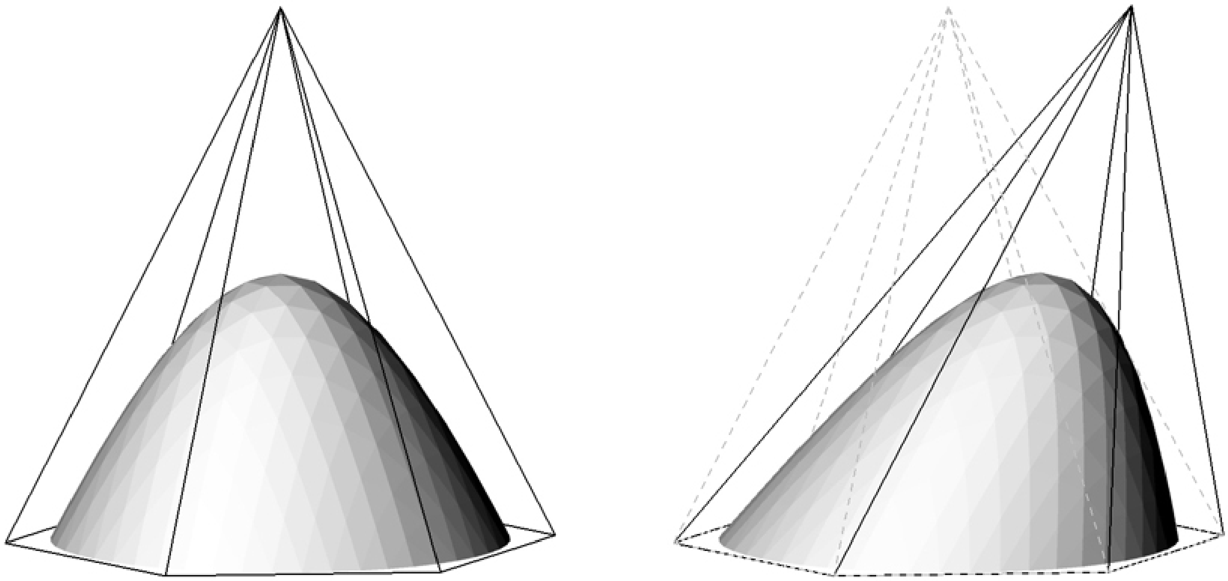

Figure 6 Generation of dome options by leaning to north.

A solar-gain calculator was then introduced into the model, which calculated the relative position of the sun for any given time of day on any day of the year. Ray-tracing was then performed to assess the amount of solar energy reaching the dome, including self-intersection of the surface to take into account when the structure would cast shadows on itself. Glazing properties were also included to account for reflection and absorption of solar energy. Solar gain values for mid-summer and mid-winter were calculated (as shown in Figure 7) and the calculations were summed over the year to give a total annual solar gain value.

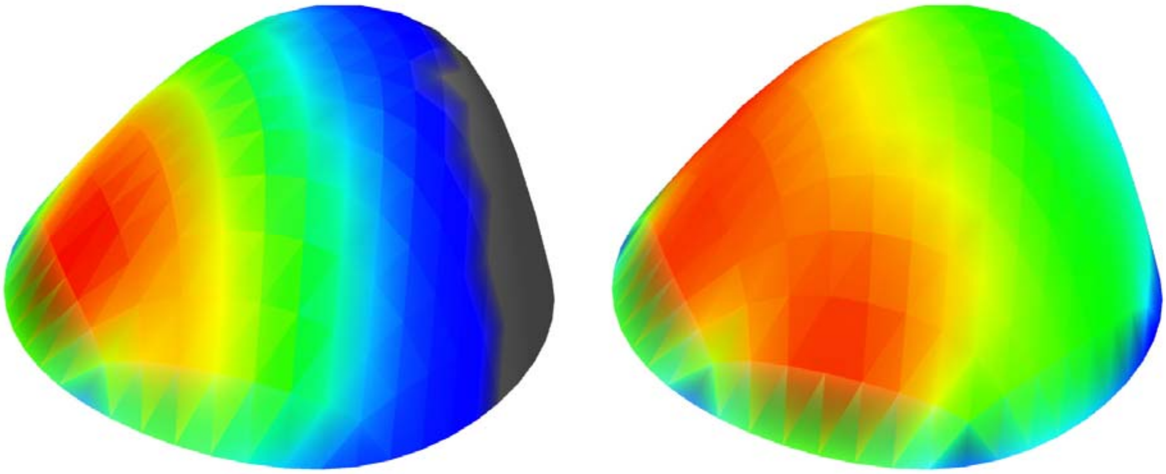

Figure 7 Solar gain plot for winter (left) and summer (right).

By using the environmental analysis in conjunction with the subdivision surface generator, the effects of changing the building's shape on its solar performance could quickly be assessed. Studies on the effects of leaning the dome to the north or south (Figure 6), stretching the footprint to the east-west or north-south (left of Figure 8), and squashing the shape to increase its volume (right of Figure 8) were all conducted quickly and an optimal design was found. This final design won the international architectural competition and construction is now under way, with the finished building due for completion in 2012.

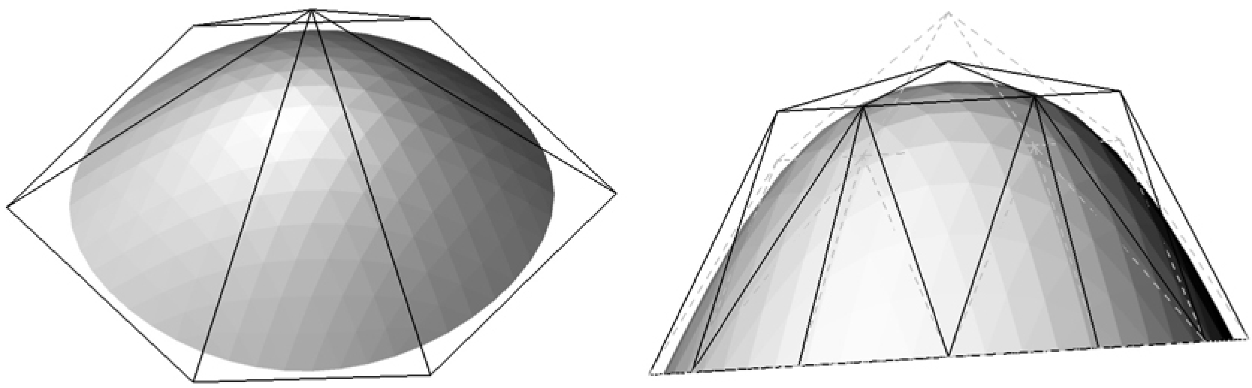

Figure 8 Generation of dome options by stretching east-west (left) and bulging to increase volume (right).

Optimisation for Structural Performance

As well as providing an efficient way of generating supporting structure for a building façade, the subdivision framework can also be used to analyse and optimise structural performance.

The subdivision mesh provides a natural method of dividing up the surface into panels which suggest regular arrangements of supporting structure. Structural members can be created along every edge (left hand side of Figure 9), or along only subsets to create patterns (centre of Figure 9). Similarly a hierarchy of primary, secondary and tertiary members can be created (right hand side of Figure 9). Alternatives can also generated by intersecting the subdivision surface with planes in various orientations to generate different structural grid options. All these methods were investigated for the Aarhus Botanical Garden project design.

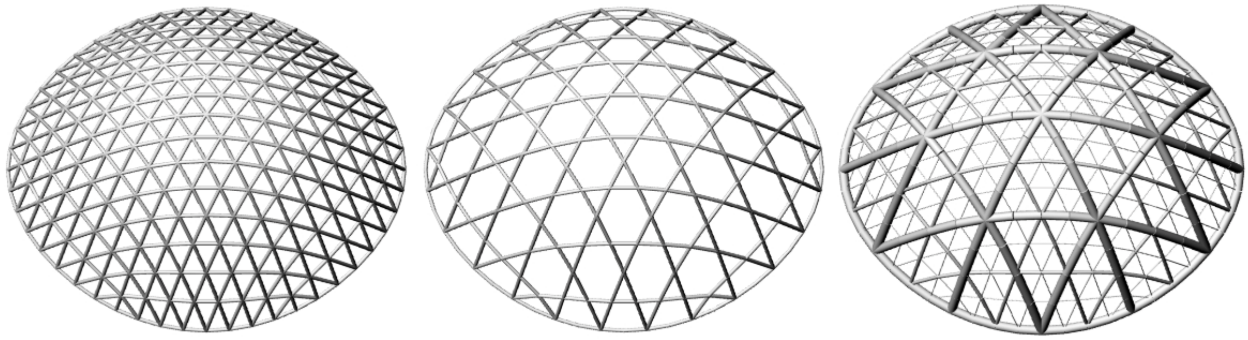

Figure 9 Options for supporting structure using subdivided mesh.

Additionally, draping simulation solvers have been included in the software framework which can take a regular grid and drape it over the subdivision surface. This can be used to generate a structural solution where each member of the grid has a fixed length to simplify construction. Growth algorithms have also been introduced whereby structure could be recursively introduced along the edges and the results from the environmental analysis used to inform the process, ensuring structure avoided areas of the façade where solar penetration was required. And by linking to commercial structural analysis software through programming (COM) interfaces, the structural performance of each design option could be automatically assessed in terms of stresses within the members for a given idealised load case. This was applied in repeating cycles to iteratively remove unstressed members until an optimal layout of supporting structure could be found. All these studies are shown in Figure 10.

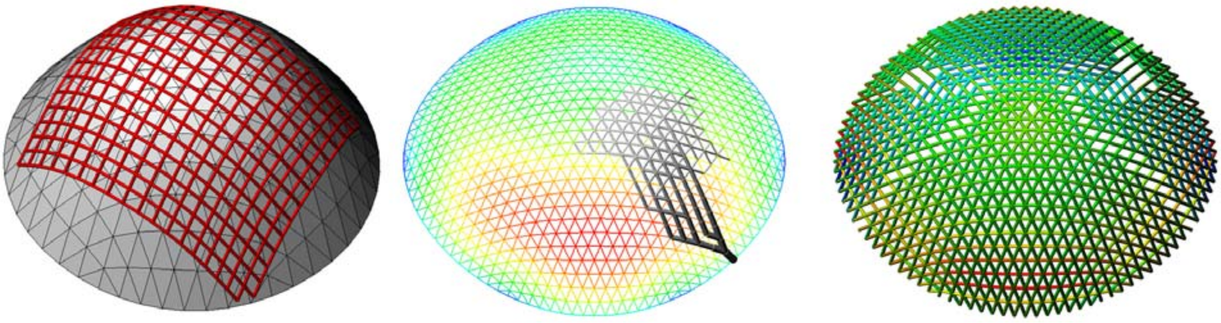

Figure 10 Draping, growth algorithms and stress calculations used to generate structural options.

Conclusions

Subdivision surfaces have been shown to posses many desirable properties for use to represent building façades during the design process. They result in smooth, aesthetically pleasing forms, but can be created using very minimal description in terms of coarse control meshes. They can be sampled at the various levels of detail required for efficient environmental and structural analysis, and used to drive automatic shape optimisation. By providing up-front information on the down-stream consequences of design decisions, more efficient holistic designs are possible and collaboration amongst the design team is facilitated.

The Digital Architectonics research group is developing new subdivision surface modelling techniques specifically for use in architectural design, as well as adding further analysis and multi-objective optimisation tools into an integrated design software framework. To be of even more practical use to the building designer, the subdivision modelling tools for generation and constraint already implemented will be extended. This will include adding lofting and creasing functionality, a parametric modelling engine and conducting research into subdivision Boolean operations. Currently, the software is capable of environmental analysis in the form of solar gain calculations and rudimentary acoustic modelling, but future plans include wind-flow, power-generation and quantity-survey capabilities. Structural analysis will be extended to include finite element analysis and topology optimisation, as well as more detailed modelling of specific material behaviours.

Through this work, new software tools will be made available to the façade engineer, to help realise sustainable, complex-geometry buildings, with an in-built efficiency without compromising on aesthetics.