Digital Architectonics in Practice

Aarhus Botanical Garden Hothouse Competition

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Abstract. Digital Architectonics is a term which refers to the application of digital technology to the architectural design process. This paper presents a new Digital Architectonics software tool, which allows various methods of 3D modeling, formfinding and optimization to be combined to generate and develop concept- and scheme-design options. The practical use of the software is demonstrated through the case study of the recent architectural competition to design a new hothouse for the Aarhus University Botanical Garden.

Keywords. Digital Architectonics; Subdivision; Optimization; Formfinding; Aarhus.

Introduction

The Digital Architectonics Research Group in the Department of Architecture and Civil Engineering of the University of Bath, UK is currently involved in a project sponsored by Informatix Inc. to develop software tools for use in the construction industry. The research focuses on the use of subdivision surface modeling techniques more usually used in computer gaming and animation industries, and has adapted these techniques to aid the design of efficient and elegant building forms.

The applicability of this research to practice has been demonstrated through its use by the winning team in the architectural competition to build a new hothouse for the botanical garden of Aarhus, Denmark.

This paper gives a very brief outline of the software and its capabilities, and goes on to demonstrate its practical use in detail through the hothouse case-study.

Research software framework

The research framework is based around answering two questions. Firstly, what benefits can subdivision surface techniques bring to the building design process, and secondly how can up-front information regarding a structure's environmental and structural performance improve such a design. In order to explore these questions a basic software application has been created using the C#.NET programming language on a Windows platform using the Tao OpenGL graphics framework (http://docs.taoframework.com/: May 2009). The program models three-dimensional geometries using mesh type constructs (vertices, edges, faces and quads) and has a wide range of data exchange capabilities through data file and direct COM interfaces with commercial software packages (currently Rhinoceros for model creation and rendering, Robot Millennium for structural analysis). Basic functionality such as model creation, editing and transformation tools (translate, rotate, scale and offset combined with move or copy) has also been included.

A subdivision surface is a detailed representation of a smooth surface geometry by a coarse control mesh. Each facet of the original mesh (be it triangular or quadrilateral) is recursively divided into smaller faces by introducing new vertices along the mesh edges and placing these new, child vertices at weighted average positions relative to the surrounding parent vertices. As the level of recursive subdivision of a mesh is increased, the mesh converges to a limit surface. The process can be thought of as a mesh smoothing algorithm since the positions of the new vertices are carefully calculated to deliver a limit surface of smooth (G2) continuity. It is this limit surface which is the focus for the current research, the idea being to use the subdivision limit surface as a building envelope. A more detailed explanation of subdivision surfaces is outside the scope of this paper, but an excellent introduction can be found in Zorin et al (2000).

Since the proposed surface is guaranteed to be smooth, but at the same time defined from a coarse control mesh, it is proposed that these techniques will provide a sketch-like environment in which to easily explore aesthetically pleasing design options. However, the second focus of the research is to identify ways of introducing efficiencies very early into the design process. Here, the principles of concurrent-engineering are embraced, whereby knowledge of the down-stream performance of the resulting structure is brought forward and presented to the designer during this early design exploration. Solvers using finite difference, force-density and dynamic relaxation techniques (Tibert and Pellegrino, 2003) have been incorporated into the software to provide methods of formfinding the initial control mesh. This can lead to structurally efficient shapes as well as being useful tools for model creation. Other performance measures such as the automatic calculation of solar gain values and calculation of building quantities have also been introduced to provide feedback on the likely impact of design decisions on the environmental impact of the proposed structure.

A full, detailed description of the software and its capabilities can be found in Shepherd & Richens (2009).

Case study

In 1969, C.F. Møller Architects designed the iconic greenhouse in the botanical garden of the University of Aarhus, Denmark. Recent plans to develop the site by combining the renovation of the existing greenhouse complex with the construction of a new tropical hothouse culminated in an architectural competition held in November 2008, with six teams of consultants proposing different designs for the hothouse.

The author was invited to join a team comprising C.F. Møller Architects and Søren Jensen Consulting Engineers, to see if the research software could inform the design process and help to produce a more optimal design solution. By providing a simple way to model complex geometrical objects, and providing detailed feedback on the suitability of each design solution, the team was able to use the software to quickly refine their design parameters. The resulting structure, being both architecturally pleasing and environmentally efficient, went on to win the competition, is now being designed for construction, and is due for completion in 2012.

Building envelope

The architectural concept for the hothouse was to produce a large domed structure to house tropical palm trees. The internal environment needed to be carefully controlled to ensure the right conditions for such plants to grow. In order to reduce heating requirements in winter, solar energy was to be allowed to enter the building through the skin. However, this should not be at the expense of allowing too much sunlight into the building during summer, which would require mechanical cooling to prevent overheating. Since Aarhus is around 57° north of the equator, there is a considerable variation in sun angle between summer and winter, so these two goals are not necessarily contradictory. A very quick way of generating alternative designs was therefore needed, along with a method for assessing each option’s environmental performance against a number of criteria.

Geometry

The subdivision surface modeling tools available in the research software were able to generate dome-like limit surfaces from a very coarse control mesh. The initial geometry of the dome was modeled using seven control points, six around the base of the dome in a hexagonal shape with a seventh vertex above the centre to create a hexagonal-based pyramid form as the solid black lines show in the left hand side of Figure 1. The resulting limit surface of this pyramid, shown shaded in Figure 1, is a smooth dome shape, and could therefore be used to represent a building envelope for the hothouse project.

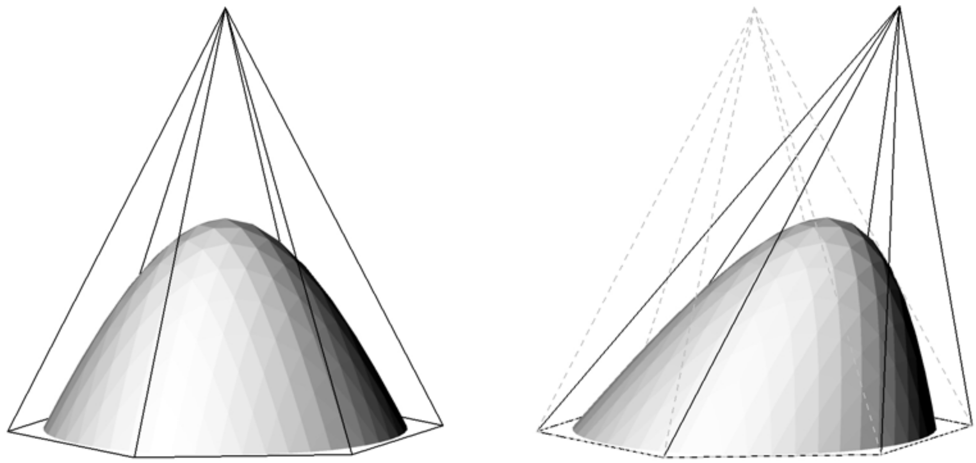

Figure 1
Basic dome shape (left) with leaning dome (right)

The limit surface is completely defined by the seven vertices of the control mesh. Therefore the designer can easily manipulate the resulting form by simply moving the control points, and can be sure that a smooth domed shape will result. For example by dragging the vertex at the top of the pyramid to the north with the mouse, the dome represented by the limit surface also begins to lean to the north but remains smooth. In a similar manner, the six vertices around the base could be moved vertically to match the slope of the landscape.

In order to accommodate the required number of large plants inside, a greater enclosing volume was required without a corresponding increase in height (to comply with planning restrictions) or surface area (to limit cost). The dome was required to bulge outwards more, and this was achieved by subdividing the control mesh once, which produced new vertices but represented the same underlying limit surface. These new vertices were then be manipulated to change the limit surface. For example the new vertices were translated upwards whilst the apex vertex was translated downwards as shown in Figure 2. Automatic quantity calculation routines reported the surface area and enclosed volume of the limit surface to keep the designer informed of the consequences of each design decision.

Similarly, the footprint of the dome was changed from a circular type shape to a more elliptical form by moving the control points around the base outwards in either a north-south or east-west direction as shown in Figure 3.

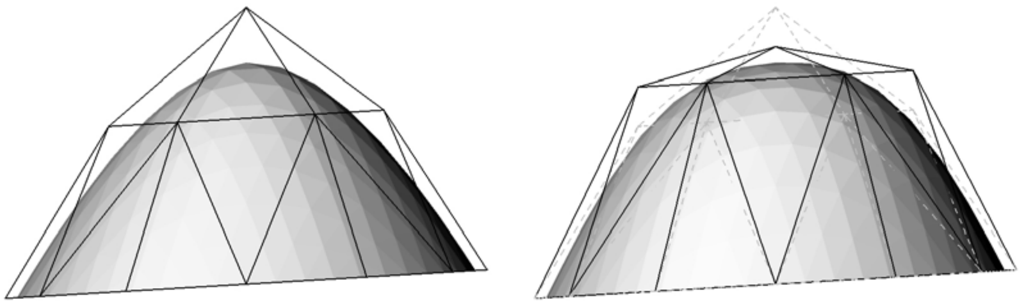

Figure 2
Subdivided control mesh (left) with modified control mesh (right) leading to a more bulging limit surface

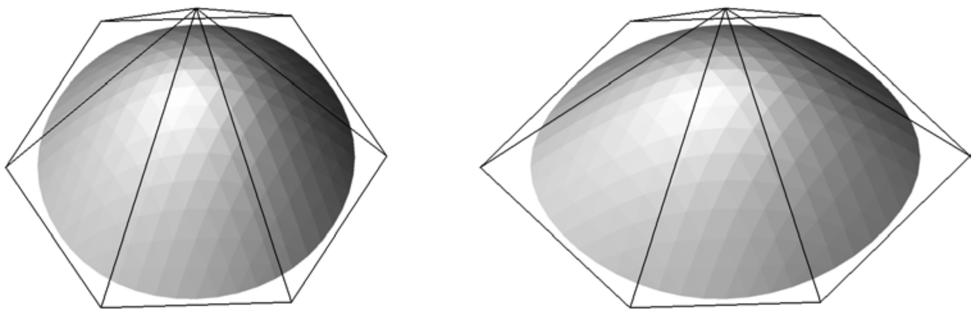

Figure 3
Regular control mesh (left) with elongated control mesh (right) giving a more elliptical limit surface

Optimization

With a simple control mesh instantly generating a smooth dome-like subdivision surface, many possible design surfaces could be generated very quickly. In order to assess the viability of each one, analysis tools were developed to provide information on the performance of each option against pre-determined criteria and to help drive the design process towards an optimal solution.

Since the geographical location of the proposed site was known, and the position of the sun at any particular time of day and day of the year can be calculated (http://ecotect.org/wiki/Solar_Position_Calculator: May 2009), a tool to calculate the amount of solar radiation reaching the building skin (represented by the limit surface) was developed. This tool traced parallel rays from the sun and intersected them with the subdivision limit surface to assess the angle with which the ray hits the dome. This information was then used to ascertain how much of the sun's energy would be reflected away and how much absorbed by the building. The ray-tracing algorithm was further refined to test for multiple intersections so that the limit surface could cast shadows on itself. The resulting solar energy penetration values were rendered using a color scale and displayed in the software. These calculations were performed hourly and integrated over a full day in mid-summer and mid-winter as Figure 4 shows. Similar calculations were performed to give typical solar gain values for an overcast sky which were reported alongside assessments of surface area and enclosed volume. These calculations were carried out for each design option and the performance of each option was given a score against a base model according to whether each measure was being maximized (winter gain, overcast gain and volume) or minimized (summer gain and surface area). The scores for each category were weighted in importance by the engineering team, leading to an overall performance measure for each design option.

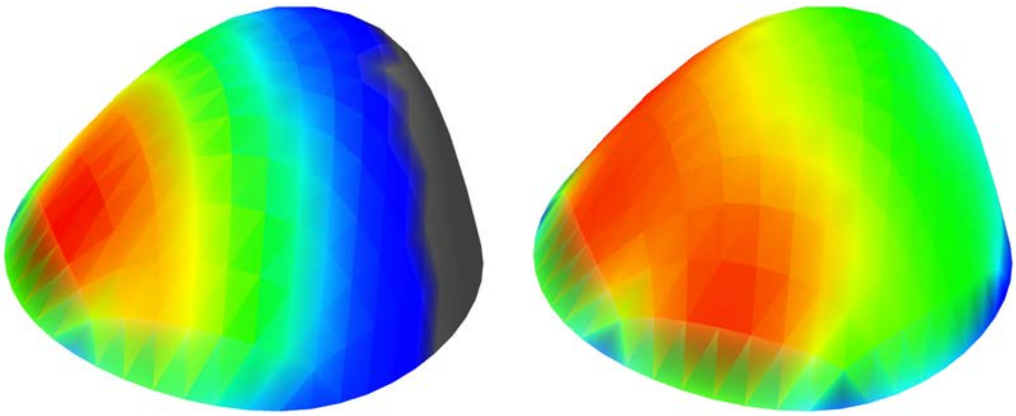

Figure 4
Total solar gain during a day in winter (left) and summer (right)

This automation of performance feedback allowed a sophisticated parametric study to be performed, whereby the effects of changing the building envelope could easily be visualized and quantified. Leaning the dome to the north, for example, exposed a larger area to the southern sun, as did stretching the footprint in the east-west direction. Creating a bulge in the dome greatly increased the enclosed volume without significantly increasing the surface area. All these measures improved the environmental performance of the proposed building envelope. At each stage the current design proposal could be communicated to the rest of the design team by exporting a VRML file for 3D rapid-prototyping in color, where the geometry represented the shape of the proposed dome (to scale) for insertion into the architect's scale model of the site context, and the colors indicated the distribution of solar energy absorption over the surface.

Structure

Once the preferred building shape had been selected, a suitable structural system had to be determined and materials chosen to deal with constructability issues and allow structural members to be sized. For both architectural and engineering reasons, a structural solution of steel supporting members and an ETFE foil cushion skin was chosen. This led to the question of how to divide the dome surface into a structural grid and how to represent the foil cushion geometry for rendering.

Grid

Many different methods of applying a structural grid to the limit surface were investigated within the research software. The most obvious was to use the triangular mesh generated by the subdivision process itself. Each level of subdivision generates a larger number of smaller facets, so various sizes of facet can be easily generated and the subdivision process continued until the panel size is suitable for the chosen cladding type, as shown in Figure 5. This procedure for generation possible structure can be further developed by only selecting subsets of all the possible edge members for construction. Patterns were generated be removing edges, and a hierarchical system was developed where some edges were chosen to represent large structural members (primary structure) and others smaller members (secondary structure), as shown in Figure 6.

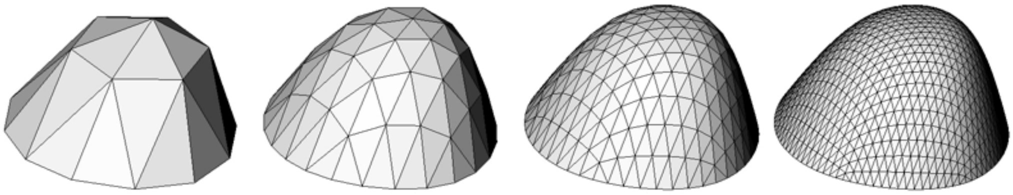

Figure 5
Limit surface sampled at increasing levels of subdivision results in decreasing panel sizes

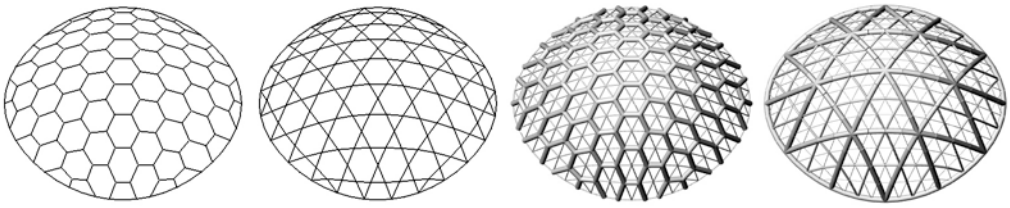

Figure 6
Selective member inclusion (left) and member-hierarchy (right) schemes for supporting structure

Other, more advanced methods for generating structure were investigated as shown in Figure 7. Recursive growth algorithms were implemented, whereby tree-type structures were grown from the base. The algorithms were directed by the previously calculated solar incidence values of the limit surface, to ensure that areas of high solar gain were not obstructed by dense structure. An iterative method of member removal was also introduced into the program through interaction with structural analysis software using a COM interface. The research software was able to start up an instance of the Robot Millennium program, automatically populate it with a structural model of the represented geometry and analyze it for an idealized (self-weight) load. The results were then read back into the research software, which was able to delete the least stressed members that were not being utilized and the process repeated. Since the whole procedure was automatically controlled by the software, the cycle could be repeated until all members were being used. Although these investigations into structural optimization did not lead to any sensible design options in themselves, they were very informative of how the dome was behaving structurally, and the functionality is now present in the software for future research projects.

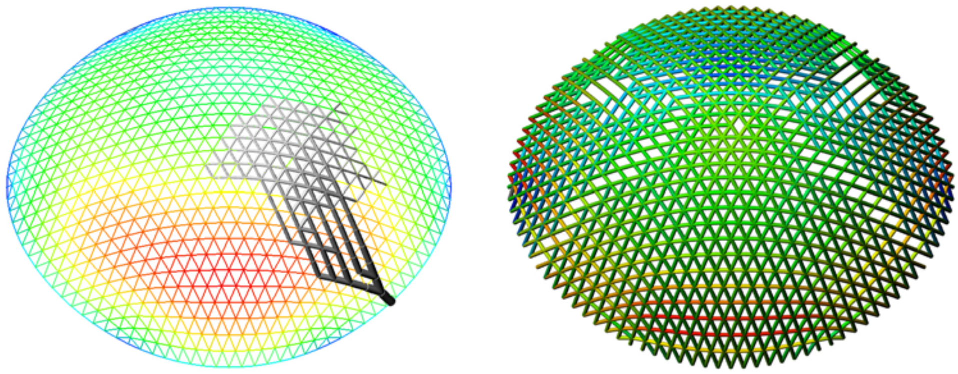

Figure 7
Recursive growth algorithm (left) and iterative removal of unstressed members (right)

The final design for structural support was a generated by intersecting the limit surface with two, orthogonal sets of planes in a radial fan. The software facilitated parametric studies on the angles and centers of rotation of the planes. The decision for the final scheme was based on engineering principles for sensible spans and member- and panel-sizes as well as practical consideration of the function of the building.

Cushions

In order to generate the pillow-effect of the ETFE foil cushions, the basic mesh elements were converted to quadrilaterals and further subdivided to produce a fine mesh for formfinding. The effect of an internal pressure was then simulated using the dynamic relaxation solver to inflate the skin in between fixed vertices along the lines of the structural frame. A positive pressure caused the skin to bubble outwards to form the outer cushion layer and a negative pressure formed the inner layer as shown in Figure 8.

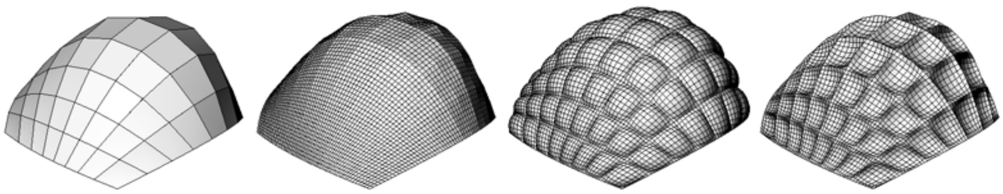

Figure 8
Subdivision to generate cushion mesh (left) and formfinding under positive and negative pressure (right)

Conclusions

Through this first practical application of the research software, the benefits of a Digital Architectonic approach to building design have been clearly demonstrated. Subdivision surface modeling techniques have been shown to easily allow creative experimentation with complex building forms. The benefits of a holistic approach to software design have been outlined, whereby many disparate tools are delivered in one single application so that each can manipulate the same model. And the adoption of a concurrent engineering philosophy has been justified through the optimization of an initial shape for structural and environmental performance. This project has also highlighted an academic and industrial partnership which has led to the successful, competition winning, innovative and efficient design, shown in Figure 9.

Mode of collaboration

The success of this project was to a large extent due to the very close collaboration between the specialist researcher, expert engineering team and innovative architectural team. Conversely, involvement in this live project was immensely helpful in moving the research itself forward, by posing unforeseen questions and introducing realistic design constraints.

Although the developmental nature of the software meant that the rest of the design team could not use it directly, having access to its functionality and an easy method of exchanging data between parties meant that they could easily generate many design options and quickly assess the relative merits of each one against their own set of criteria. The single design model necessitated strong collaboration, which more than made up for any possible bottleneck in terms of the design process.

Figure 9
Final render of existing greenhouse (left) with new hothouse dome (right)

Future direction of research

Although the current prototype nature of the software prohibits its use by non-specialists, the ultimate aim is to develop a more user-friendly application which would benefit every engineering and architectural practice in the design and optimization of complex geometry buildings. It is proposed that such software can facilitate a closer collaboration between architects and engineers and its use will soon become standard practice within the building design process, rather than a specialism reserved for experts.

The future work of the Digital Architectonics research group will focus on extending the use of subdivision surfaces in building design, especially looking at the open question of how to perform Boolean operations. The range of optimization algorithms will also be extended and a more robust parametric modeling framework introduced.

Acknowledgements

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