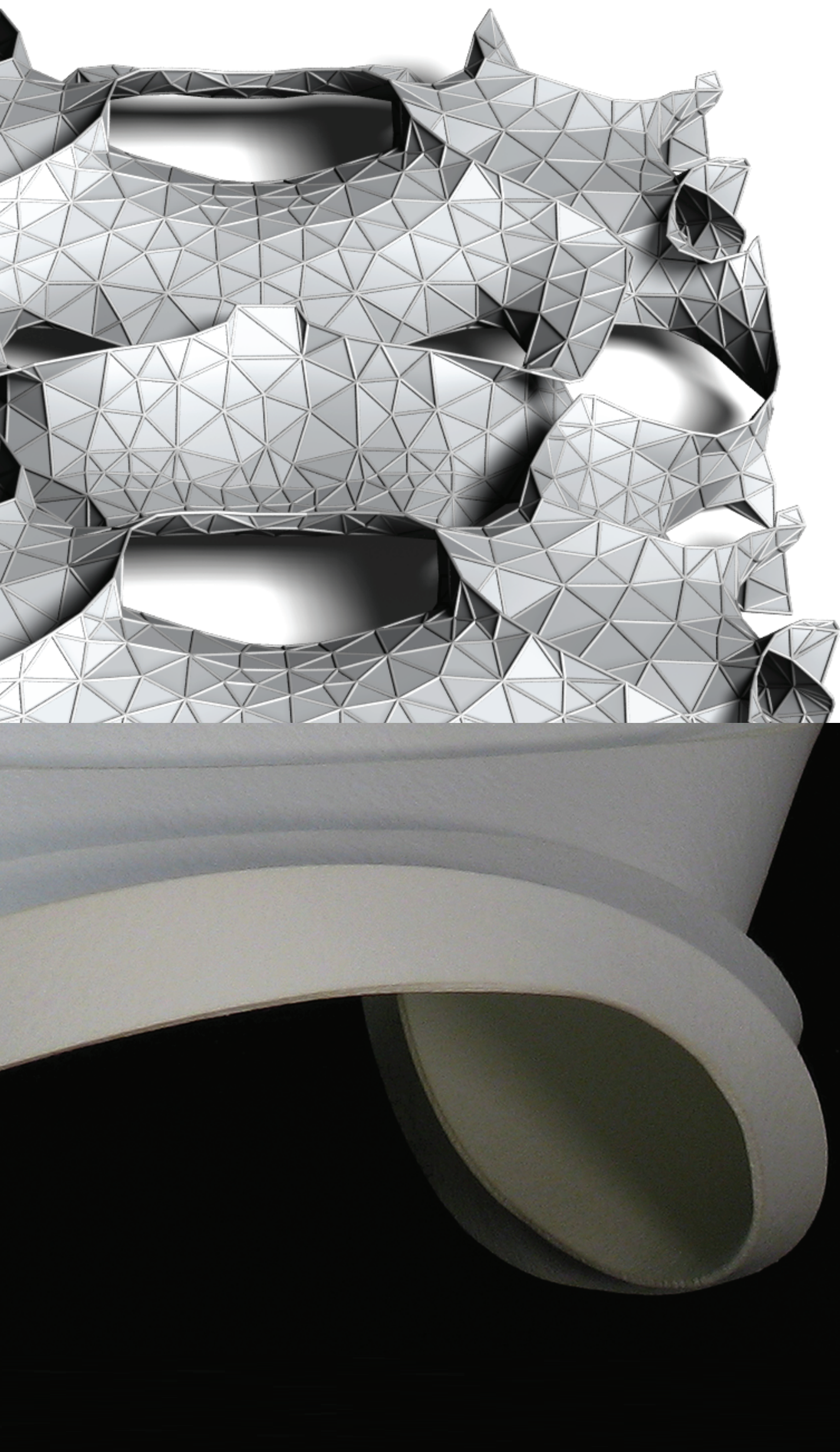
Advances in Architectural Geometry

Vienna, Austria September 13-16, 2008



Conference Proceedings

AAG 2008

Advances in Architectural Geometry 2008

First Symposium on Architectural Geometry
Vienna, Austria
September 13-16, 2008

Conference Co-Chairs:

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Preface

Geometry lies at the core of the architectural design process. It is omnipresent, from the initial form-finding stages to the final construction. Modern geometric computing provides a variety of tools for the efficient design, analysis, and manufacturing of complex shapes. On the one hand this opens up new horizons for architecture. On the other hand, the architectural context also poses new problems to geometry. Around these problems the research area of Architectural Geometry is emerging. It is situated at the border of applied geometry and architecture.

A research area being so interdisciplinary as Architectural Geometry and involving fields as diverse as art and design, computer science, engineering and mathematics, needs scientific exchange. Advances in Architectural Geometry 2008 is our first attempt in bringing together researchers from these fields to discuss recent

advances in research and practice and to identify and address the most challenging problems. We aim at connecting researchers from architectural practices and academia.

AAG 2008 received 56 submissions which have been reviewed by the members of the Scientific Programme Committee. The specific cultures in the involved scientific communities often resulted in a high variation of grades the same paper received by reviewers from different areas. This made the selection process particularly difficult.

We decided to accept only a small number of papers for oral presentation, since a low number of presentations offers sufficient time for discussion, which is essential for this first conference on Architectural Geometry. At this point, we would also like to thank the members of the Scientific Programme Committee for their excellent

and mostly timely reviews which had to be performed during a quite short time span.

Extended abstracts of the 14 accepted papers form the content of the present

proceedings. The copyrights remain with the authors and thus publication of the full version of the papers elsewhere poses no problems.

The variety of research areas and the balance between academia and architectural practice is also reflected in our choice of invited speakers: Konrad Polthier (FU Berlin), Carlo Sequin (UC Berkeley), Dennis R. Shelden (Gehry Technologies, LA), Charles Walker (Zaha Hadid Architects, London) and Arnold Walz (designtoproduction, Zürich). We are very grateful to them for accepting our invitation and sharing with us the most recent results of their research.

This event would not have been possible without the help of many friends and colleagues. Special thanks belong to our conference secretary Natalie Klement for her help with all organizational issues and to our conference technician Ronald

Haidvogl for his technology support. We greatly appreciate the important support in early organizational issues by Werner Purgathofer and Anita Mayerhofer.

Furthermore we would like to thank Martina Milletich from the Austrian Academy of Sciences for a very smooth handling of all our requests.

Last but not least we would like to express our sincere gratitude to the sponsors of this conference: RFR (Paris) and Waagner Biro Stahlbau AG (Vienna). Their generous support greatly reduced the registration fees and thus helped to attract many more, especially young people to this first conference on Architectural Geometry.

The conference is also supported by the Austrian Science Fund (FWF) under grants NFN S92 “Industrial Geometry”, P18865 “Constrained Optimization with Geometric Objects” P19214 “Discrete Surfaces with Application in Architectural Design”, FFG project Nr. 813391 MLFS “Multilayer Freeform Structures” and TU Wien.

We hope that all participants of this symposium as well as the readers of these proceedings will enjoy the program of AAG 2008 and look forward to a future workshop and conference on Advances in Architectural Geometry.

Helmut, Axel and Michael

Sponsors

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Algorithmically Acquired Architectural and Artistic Artifacts

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Abstract

Various approaches to create geometrical shapes by procedural means are described for applications in art and architecture. Some examples are given, ranging from conceptual building shapes, through modular wall elements, to abstract geometrical sculptures.

Keywords: computer-aided design, architectural building blocks, abstract sculpture, procedurally generated geometry, design for ease of realization.

1 Introduction

In almost all design tasks today computers are playing an ever more prevalent role. They allow designers to quickly explore a much larger solution space; they help predict the final outcome more accurately; they make redesign tasks less tedious; and they permit to take realization concerns into account at an earlier stage.

I have had opportunities to work on a variety of quite different design tasks ranging from integrated circuits and solid state cameras to mechanical puzzles and institutional buildings. In most of these designs I focused on their geometrical aspects. In all cases the computer was used to actively support the creation of geometric shapes by procedural means; and modularity and reuse of parameterized components played an important role.

In the 1990s I began to interact and collaborate with several artists, but primarily with Brent Collins, a wood sculptor who creates intricate and highly symmetrical abstract geometrical forms. It was natural for me to try to apply similar computerized design techniques in this new domain.

2 *Sculpture Generator I*

My interaction with Collins started when I encountered a photo of his *Hyperbolic Hexagon* (Fig.1a) [COLLINS 1997]. Seeing his intriguing, highly structured sculptures, I wanted to understand their underlying generative paradigms. One way to interprete Figure 1a is to describe it as a ring of six consecutive hole-saddle combinations, like the ones in the center of Scherk's 2nd minimal surface (Fig.1b) [SCHERK 1835].

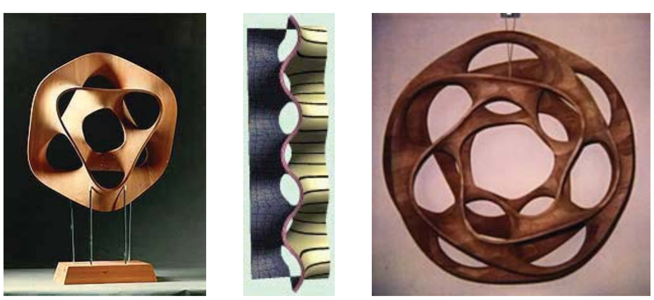

Figure 1: (a) *Hyperbolic Hexagon*, (b) 7-story *Scherk Tower*, (c) *Heptoroid* (seven 4th-order saddles).

Generalizing this paradigm, we might want to change the number of hole-saddle combinations and possibly add a twist to the whole chain, before it is closed smoothly into a toroidal loop. In my first phone conversation with Collins, we already deduced that if the number of hole-saddle combinations was odd, the resulting surface would be single-sided, and the edges on that surface would form interesting torus knots. While we could figure out quickly the consequences of adding more stories or different amounts of twist, it was not so clear, what aesthetic merits these geometries might possess. This prompted me to build a special-purpose visualization tool for this kind of geometry; I called it *Sculpture Generator I* [SÉQUIN 1997]. A dozen sliders allow me to explore interactively many different combinations of topological and geometrical parameters, and thus find out whether some intriguing conceptual geometries also have enough aesthetic merits to warrant turning them into a sculpture. The most promising shapes can then be fine-tuned and optimized for their visual appeal as well as for their manufacturability. This program has turned out to be very useful. Dozens of sculptures of various sizes have emerged from it, and many people have downloaded it and have used it for their own experiments. The drawback is that it is a very special-purpose program; it can only create twisted and bent hole-saddle chains.

3 Paradigm Extensions

Although *Sculpture Generator I* is based on only one single geometrical module that gets bent, stretched, twisted, and reused in many different ways, it can produce an amazingly wide variety of different sculptural shapes. After I had the basic program running in 1995, I introduced several different paradigm extensions over the following years. The simple biped saddles was replaced with saddles of higher branching orders (Fig.1c). Affine stretching of the toroids produced totem-like sculptures (Fig.2a). Letting the hole-saddle chain loop around the toroidal ring more than once led to intricate interleaved structures (Fig.2b).

Figure 2: (a) *Totem 4* sculpture, (b) doubly-wound toroid.

4 *Pax Mundi* and SLIDE

In 1995 Collins created another inspirational sculpture (Fig.3a), for which I suggested the name *Pax Mundi*. I urgently wanted to experiment with forms like this at interactive speeds. But there was no way that *Sculpture Generator I* could produce such shapes; thus a new paradigm had to be found. By construction, Collins had created this shape as a ribbon undulating around a sphere. Hence it was natural to generate this shape as a sweep along a curve embedded in the surface of a sphere. The dominant undulations reminded me of the edges in sculptures by Naum Gabo, and I thus defined an "*n*-lobe Gabo curve" as a generalization of a baseball seam: a meandering curve completing *n* full cycles as it traverses around the globe along the equator. This curve was parameterized not only by the number of its cycles, but also by the amplitudes of the individual lobes, and by their width and pointiness (Fig.3b).

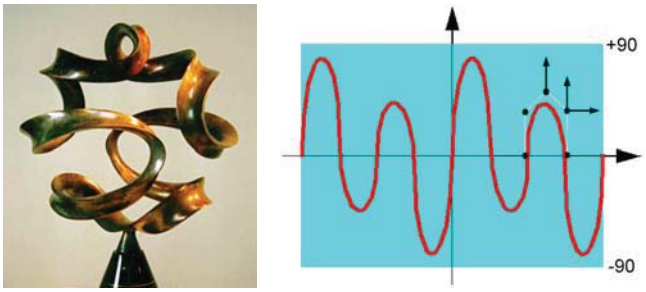

Figure 3: (a) *Pax Mundi*, (b) modulated 4-period Gabo curve.

In this particular "sculpture generator" we also need to specify its cross section, and the way that it is rotated and scaled as it is swept along the base curve. Rather than writing another stand-alone program for generating sculptures of this kind, I used our modular modeling environment, Berkeley SLIDE [Smith 2003], which already had a powerful sweep generator with all the necessary controls. Thus I just needed to add two modules for specifying the sweep curve on the sphere and for specifying a cross section. With these elements in place, it was then easy to generate a wide variety of such *Viae Globi* ("*Roads-on-a-Sphere*") sculptures (Fig.4a). A few years later I could also easily accommodate a paradigm extension that moved the sweep curve away from the sphere surface and allowed it to make internal loops, in order to emulate Collins' *Music of the Spheres* sculpture (Fig.4b).

Figure 4: (a) *Via Globi - Maloja*, (b) *Music of the Sphere*.

5 Reverse Design and Creativity

The previous examples were trying to illustrate a new form of creativity. Rather than creating one instance of a beautiful shape based on intuition or some holistic right-brain activity, we are now seeking the creative skill to look at a beautiful shape and then come up with a generative principle that will procedurally create that shape. This generating paradigm should be structured so that it can be parameterized with the goal to produce other similar shapes, and possibly whole families of them. Defining the number and function of these parameters is a crucial and non-trivial task. If there are too few, the application domain is too narrow. But if there are too many, the program loses all structure, and it no longer offers any advantage over modeling with individual surface patches. Defining such novel sets of cooperating generator modules is a new form of creative expression.

6 Minimal Surfaces and *Volution* Shells

Many of Collins' sculptures have smooth saddle surfaces resembling soap films suspended in a curved wire frame. These "almost-minimal" surfaces were not designed by mathematical techniques but were carved intuitively, un-assisted by any technical design tools. In a computer-based design environment, Collins' artistic intuition needs to be replaced with a mathematical procedure. Ken Brakke's *Surface Evolver* is one such tool [Brakke 1992]. It modifies and refines triangle meshes to make them approach the shape of a minimal surface with a mean curvature of zero. For the geometrical shapes discussed in this section, all I had to do was to enter a coarse polyhedral approximation of the desired topology and to specify and adjust some geometrical constraints to prevent some of the tunnels from collapsing prematurely.

The *Volution* elements shown in Figure 5 are all based on twelve edge constraints in the shape of quarter circles, two each lying at opposite corners on the six faces of a cube. The suspended surfaces of different connectivity, ranging from genus 0 to genus 10, were inspired by the tabulation of triply periodic minimal surfaces found on Ken Brakke's webpage [Brakke 2000].

Figure 5: (a) *Volution_0*, (b) *Costa surface* of genus 2.

7 Modular Wall Elements

The elements shown in Figure 5 not only make attractive abstract sculptures, but they also can be used as modular architectural building components. One obvious composition follows from the regular periodic surfaces shown by Brakke [Brakke 2000]. However, since many different surfaces of different genus can be suspended in the same set of curved edges on the cube surface, different elements can be mixed and matched with different orientations to construct a wide variety of architectural walls, reminiscent of the work by Erwin Hauer [Hauer 2004]. Figure 6a gives an example of such a modular assembly.

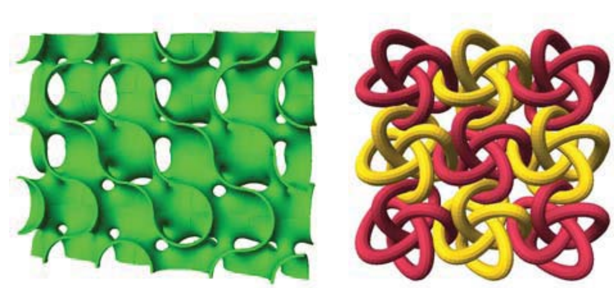

Figure 6: (a) *Volution*-wall, (b) Knot-wall.

Other intriguing elements that can be assembled in 3D space can be obtained from interlinking knots. The modular knot element itself can be generated as a sweep along a suitable curve (Fig.6b).

8 Functional-based Surface Optimization

Minimal surfaces, and surfaces that overall minimize the integral over local bending energy (MES), form rather nice default optimizations for surfaces that may be constrained only by some boundary lines, by some symmetry requirements, and perhaps by some overall constraints of their extent or of some enclosed volume. But these functionals are less ideal for high-genus handle bodies with many toroidal arms; they tend to force these arms into clusters of little pillars and tiny holes, separated by large spherical bulges (Fig.7a).

Thus it is worthwhile to look for other functionals that might make a different tradeoff and lead to a different distribution of local curvatures. In the early 1990's Henry Moreton explored Minimum Variation Surfaces (MVS), based on a functional that minimized the surface integral of the square of the **change** of curvature in the principal directions [Moreton and Séquin 1992]. It led to shapes with more distinct, nicely shaped toroidal arms (Fig.7b). Since then we have experimented with a few other functionals based on curvature changes. Pushkar Joshi has explored an MVS functional that also included mixed derivatives (Fig.7c), as well as weighted mixtures of the various functionals [Joshi and Séquin 2007]. This work will eventually lead to an environment where a designer can choose from a variety of surface optimization styles that will best satisfy his or her sense of aesthetics.

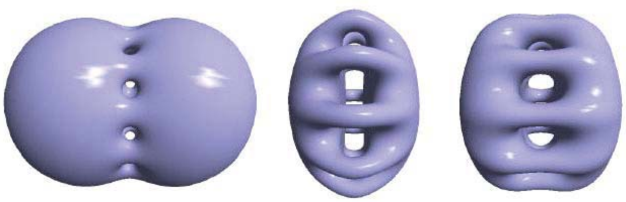

Figure 7: (a) MES, (b) MVS, and mixed optimization functional.

9 Moebius Bridges and Buildings

Below is another example how artistic geometry can also be made useful and practical. The design challenge was to design bridges and buildings in the form of Moebius bands. The two solutions shown use a powerful sweep process where the orientation of the cross section with respect to the Frenet frame of the sweep curve can be precisely controlled along the whole path. In case of the bridge, the "I-shaped" cross section is kept perfectly horizontal for the entire length of the active road bed, and then undergoes a 180° twist while passing through the arch, thus providing extra strength to support the pull of the suspension cables. At both ends an opening is cut into the I-beam to let traffic onto and off the bridge.

In case of the Moebius building, the cross section is kept vertical in the upper, S-shaped part, to accommodate several stories of apartments or offices. In the straight return path at ground level, the window facades of the upper portion turn into sky-lights for common function rooms such as, indoor atria, conference rooms, galleries, shopping malls, or sports facilities.

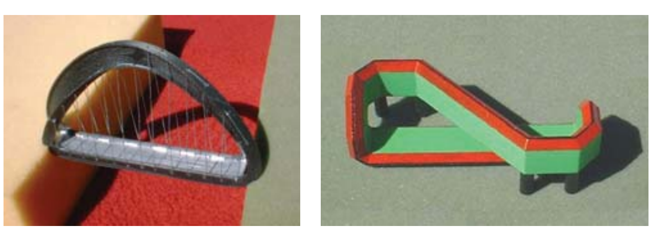

Figure 8: (a) *Moebius* bridge; (b) *Moebius* building.

10 Rapid Prototyping

In spite of the availability of ever more advanced rendering and visualization tools, physical 3D models play an important role in many design efforts. They are crucial to evaluate the tactile aspects of components such as the handles on an appliance or the grip of a hand tool. Models are useful to verify the proper functioning of a mechanism or the proper mating of parts in a modular assembly. But even for purely aesthetic artifacts, such as geometric sculptures, prototype maquettes that can be readily inspected from all sides under varying lighting conditions often reveal opportunities for further design improvements.

Most CAD tools will output a boundary representation of the designed object in the form of a triangle mesh. This can then be captured in the simple, verbose, inefficient, but widely available .STL-format, which is accepted by almost all rapid prototyping machines, and which can thus be used to produce scale models by layered free-form fabrication. Typically, the machine software slices the boundary representation into thin layers, about 0.01 inches thick. These layers are "painted" individually, one on top of another, by a computer-controlled nozzle, dispensing either some build material in a semi-liquid state, or some liquid binder substance that locally glues together loose build particles, such as plaster powder or very fine stainless steel granules. I have used such machines to produce dozens of maquettes for final design checks, but also to make the master copies that are then sacrificed in a modified investment casting process.

11 Realization Headaches

One danger with using purely geometrical design tools that are not tied in with any physical simulation tools or any verification software for the intended fabrication process is that it is easy to forget the physical aspects of the emerging construction. In 2006 Collins and I received a commission to scale up the original, 2-foot diameter *Pax Mundi* wood sculpture to the 6-foot level and to turn it into a bronze sculpture for the H&R Block headquarters in Kansas City.

Figure 9: (a) *Pax Mundi*, sagging; (b) final installation.

I took my original emulation of *Pax Mundi* and adjusted the many parameters to fit the new constraints. In particular, I had to make the ribbon more slender to keep within the specified weight limit of 1500 pounds and to reduce the amount of (expensive) bronze needed. In this work I overlooked the fact that the final sculpture, which was assembled from 20 individually cast sections by Steve Reinmuth [Reinmuth 2000], would sag by about a foot under its own weight (Fig.9a). Reinmuth fixed the problem by hanging the sculpture from its top point, cutting half-way through the ribbon at a few strategic places, and filling the wedge-shaped gaps with bronze weld. The elongated ellipsoid formed in this manner then was allowed to sag back to a perfectly spherical shape under the influence of gravity when mounted at its lowest point (Fig.9b).

12 Design for Manufacturability

Keeping the complete fabrication process in mind becomes even more important when one is asked to make many copies of the same object. This was the case in 2007 when I got the commission to design an award trophy in bronze to be handed out at the annual Eurographics conferences for a *Distinguished Career Award*, a *Technical Contributions Award*, and a *Young Researcher Award*. In total the conference management wanted about twenty copies to honor all past recipients, and they are planning to award about three more trophies in every coming year.

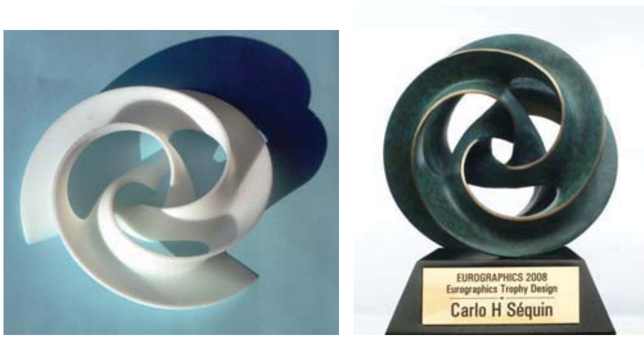

Figure 10: (a) The half-wheel master; (b) final *EG-award* trophy.

From several suggestions that I made to them, the Eurographics management chose a design based on the shape of "*Whirled White Web*," our snow sculpture that won the silver medal at the 2003 Snowsculpting Championships in Breckenridge, Colorado [COLLINS 2003]. To keep costs down, we could not afford to re-generate a new master model on a rapid prototyping machine to be sacrificed for every bronze trophy cast in an investment casting process. We had to create a master mold in which new secondary positive copies could be produced in wax quickly and inexpensively. However the shape of "*WWW*" did not lend itself for making a simple, re-usable mold; there were too many internal, hard-to-reach concavities. The problem could be ameliorated by cutting the wheel shape into two identical parts along the main symmetry plane (Fig.10a). This shape can be reproduced in a silicone-rubber mold consisting of only four parts; three identical parts below the three large "eyes" and a fourth part covering the whole top.

Two half-wheels are separately cast in wax and then combined into the full wheel. This part is then cast in bronze with the classical investment casting process. The base is cast as a separate part from a rather simple mold. The wheel is inserted into two grooves in the pedestal and spot welded to it from the inside of the base. The wheels are given different patinas to distinguish the three different awards; but the base is always black and carries the commemorative brass plaque.

Conclusion

Geometric problems are present in many phases of architectural and artistic design. Computer tools can be a great help in most phases, from initial generation of conceptual ideas, through the detailed design of the desired shapes, to the final verification of the functional and/or aesthetic validity of the proposed solution. CAD tools are most helpful today in the final phases of design, where a lot of the validation depends on much detailed, tedious computation, which humans gladly offload to machines. Today's CAD tools are probably the least helpful at the very beginning of the design process in the initial, creative phase of conceptual design. Existing user interfaces are not conducive to truly free-form thinking. The typing and/or point-and-click paradigms are poor substitutes for deforming clay or cloth, bending wire, carving styrofoam, or taping together various (possibly bent) pieces of cardboard.

In the future, CAD environment providing several haptics devices attached to both hands may enable designers to become more expressive in a free form manner. Perhaps an immersive environment that accepts a wide range of sweeping gestures and hand and finger movements will provide a better user interface. The most important factor for all such initial input environment is real-time interactivity. Tools that cannot keep up with the designer's creative thinking process will not be successful. On the other hand, tools that are based on a few high-level inputs and which can create a rich variety of shapes and immediately show the consequences of small changes in any constraints can truly become amplifiers of the designer's creative powers.

In the mid-phase of the design process, tools would be useful that allow a much more direct coupling of the design process to the constraints of the intended realization process. If the final shapes are to be made from bent sheet metal, then the tool should restrict the designer to the composition of patches of developable surfaces, possibly incorporating a cost function for the difficulty of actually rolling a flat piece of sheet metal into the desired 3D form. For artifacts that will be made with injection molding, the difficulty of mold making should be factored in and brought to the attention of the designer.

Clearly existing design tools for architects and artists still have a long way to go. But close interaction between practitioners, computer scientists, and CAD tool builders should get us there more quickly.

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Symmetry for Architectural Design

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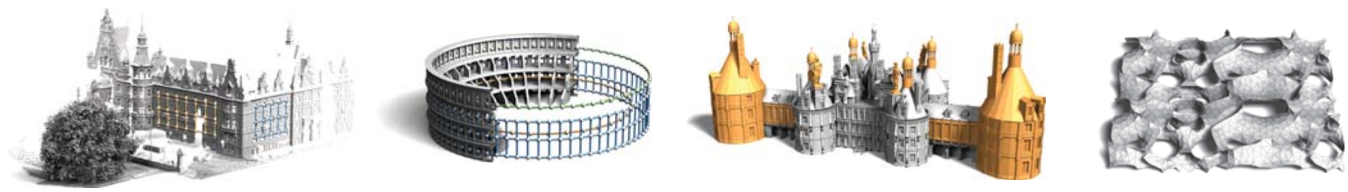

Figure 1: *Various architectural models analyzed and modified by exploiting information on shape symmetries and regular repetitive patterns.*

Abstract

Symmetry and regularity abound in architectural models, often as a result of economical, manufacturing, functional, or aesthetic considerations. We show how recent work on symmetry detection and structure discovery can be utilized to analyze architectural designs and real-world artifacts digitized using 3D scanning technology. This allows reverse engineering of procedural models that facilitate effective exploration of the underlying design space and the synthesis of new models by modifying the parameters of the extracted structures and symmetries. We demonstrate the effectiveness of such an approach on a number of example designs.

Keywords: shape analysis, symmetry, repetitive patterns, structural regularity, procedural modeling

1 Introduction

Architectural designs commonly exhibit significant symmetries or contain repetitive patterns. These types of structural regularity are not accidental, but often the result of economical, manufacturing, functional, or aesthetic considerations. Whether by evolution or design, symmetry implies certain economies and efficiencies of structure that make it universally appealing. Symmetry also plays an important role in human visual perception and aesthetics. Arguably much of the understanding of the world around us is based on the perception and recognition of shared or repeated structures, and so is our sense of beauty [Thompson 1992].

Symmetry is also fundamental in the laws of physics, hence optimality conditions in terms of statics often lead to symmetric configurations. In addition, structural regularity in architectural models allows pre-fabrication and mass-production of repetitive elements and can thus lead to significantly reduced production costs.

Recent work in 3D shape analysis has focused on detecting symmetries and regular structures in geometric models [Martinet et al. 2006], [Mitra et al. 2006], [Podolak et al. 2006], [Simari et al. 2006], [Mitra et al. 2007], [Li et al. 2008], [Pauly et al. 2008]. These research efforts offer a wealth of tools that can be employed to improve the architectural design process. In particular, explicit knowledge of symmetry and geometric regularity can be exploited to facilitate reverse-engineering of design rules for procedural modeling or symmetry-aware shape optimization. Symmetry information can also be beneficial for shape reconstruction from scanned data [Pauly et al. 2005], [Thrun and Wegbreit 2005], [Pauly et al. 2008] or images [Müller et al. 2007], [Liu et al. 2008].

In this paper, we summarize our previous work on symmetry detection [Mitra et al. 2006], symmetrization [Mitra et al. 2007], and structure discovery [Pauly et al. 2008] with special emphasis on potential applications in architectural design.

2 Symmetries and Regular Structures

Our approach is based on the techniques for finding symmetry information and repetitive structures introduced in [Mitra et al. 2006] and [Pauly et al. 2008], respectively. We briefly describe the central ideas of these methods, but refer to the papers for a more detailed discussion. Symmetry and structural repetitiveness can be formalized using the notion of invariance under transformations. We say that two parts $\mathcal{A}, \mathcal{B} \subseteq \mathcal{S}$ of a 3D model $\mathcal{S}$ are symmetric, if there exists a transformation T, e.g., a rotation, reflection, or translation, such that $\mathcal{B} = T(\mathcal{A})$. In general, we consider the space of similarity transformations composed of uniform scaling, rotation, translation, and possibly reflection. To find symmetry transformations of a given shape, we apply a sampling approach illustrated in Figure 2 that has been proposed in [Mitra et al. 2006] and, independently, in [Podolak et al. 2006].

The surface of the model is sampled uniformly with average sample spacing h. The user parameter h determines the scale of the smallest symmetric elements that we want to detect. For every sample

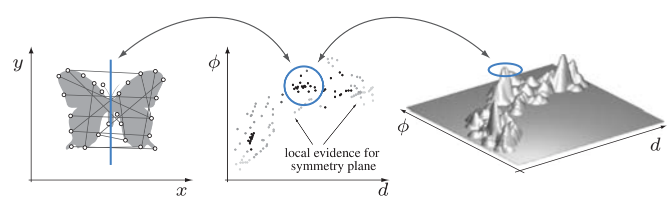

Figure 2: *To detect symmetries in geometric models, we uniformly sample the boundary of the shape (left). Every pair of samples with compatible local surface geometry provides local evidence for a symmetry transformation (center). In this example we consider reflections that are parameterized by an angle ϕ and the distance d to the origin. Accumulating such evidence using a clustering approach yields the dominant symmetries of the model (right).*

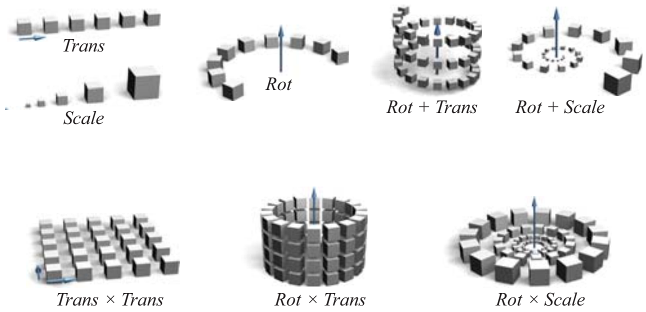

Figure 3: *Schematic illustration of regular structures. The helix and spiral are generated by transformations that combine rotation with translation and scaling, respectively. The bottom row shows the three types of commutative 2-parameter groups that can be detected with our approach.*

point we compute a local signature that compactly encodes local geometric properties at that point that are invariant under transformations of the specific transformation space under consideration. Sample points with similar signatures are paired and a canonical transformation that maps one sample to the other is computed and refined using local registration methods.

The key observation is the following: If a shape contains symmetries or repetitive structures, then the estimated transformations exhibit specific accumulation patterns when mapped to a suitable transformation space. These patterns can be extracted using clustering methods and grid fitting techniques. While the method of [Mitra et al. 2006] is mostly concerned with pairwise symmetries, the structure discovery method of [Pauly et al. 2008] in addition analyses the spatial relations among different symmetries. The underlying formulation is based on theory of transformation groups and thus allows a rigorous mathematical treatment of the concept of structural regularity. Different types of regular repetitive structures that can be detected by this method are shown in Figure 3.

The result of this analysis in transformation space is a set of symmetries and repetitive patterns that encode important medium and large scale structural information of the processed shape. Symmetries can often be represented in a hierarchy, while repetitive structures are described by a representative element, i.e., a patch $\mathcal{P} \subset \mathcal{S}$, a set $\mathcal{T}$ of generating transformations, and the number of repetitions in each dimension (see Figure 6, lower left).

3 Shape Analysis and Design

The analysis of digital 3D models using the methodology described above provides us with a compact representation of the symmetries and repetitive structures of a shape. We first show some examples and then discuss how this information can be utilized to provide effective tools for shape exploration and manipulation in the context of architectural design.

Figure 4 shows the dominant symmetries detected in a digital model of the Sydney opera. The underlying transformation space is the seven-dimensional space of similarity transformations whose elements are composed of uniform scaling, rotation, and translation.

Figure 5 shows an application of the structure discovery algorithm to raw scanner output. The point cloud has been acquired with a single-viewpoint laser scanner, which leads to gradually varying sample spacing due to perspective distortion. Despite the low sampling density and holes in the data caused by occlusion, the algorithm robustly finds two regular translational grids. The figure also illustrates how the detected symmetry information can be utilized for model repair.

Figure 6 illustrates the difference between top-down symmetry detection according to [Mitra et al. 2006] and bottom-up structure discovery using the method of [Pauly et al. 2008]. The former extracts mostly pairwise symmetries, such as the global reflective symmetry or the rigid motions mapping the towers or chimneys onto each other. The latter detects translational and rotational grids of windows and other structural elements, but ignores the chimneys, since their spatial arrangement does not match any of the repetitive patterns defined in Figure 3. On the other hand, this method is capable of discovering and compactly representing structures composed of very small elements such as the balustrade, which are not extracted by the top-down symmetry detection approach.

Procedural Modeling. A simple yet effective modeling operation is part replacement. Structural elements can be replaced or modified using standard modeling tools. The system then automatically replaces all symmetric copies to preserve the structural integrity of the model. This type of operation is illustrated in Figures 6 and 8. In addition, we can modify the parameters of the regular structures, e.g., the number of repetitions as illustrated in Figures 7 and 8. This type of procedural design allows the user to quickly create variations of an original design or scanned artifact that would be tedious to achieve with traditional modeling tools.

Symmetrization. The extracted symmetries are often not perfect in the sense that the transformed part $T(\mathcal{A})$ might not exactly match the corresponding part $\mathcal{B}$. This occurs, for example, when scanning a real-world object due to the discrete sampling process, or when the model itself is not perfectly symmetric, e.g., a partly preserved ruin. In addition, many physical architectural prototypes or design studies are often not build with high geometric accuracy, so that a digitized model might not possess all the intended symmetries. To enhance approximate symmetries we can employ the symmetrization approach of [Mitra et al. 2007]. As illustrated in Figure 9, this method can be used to generate symmetric meshes, which can be important if the mesh represents structural elements such as struts or beams, e.g., in a steel-glass construction.

4 Conclusion and Future Work

We discussed how symmetry and structure discovery algorithms can be exploited for shape analysis and synthesis in the context of architectural design. These tools provide a first step towards a more comprehensive framework for procedural modeling based on reverse-enginerring of shape design rules. The analysis of symmetry and repetitive structures can also be utilized in the classification of buildings from different historical periods and potentially provide insights into the style of a specific architect or designer.

The modeling operations of the above examples solely rely on geometric information and thus do not take into account semantic information that might be important to adequately represent the underlying design intent. An important avenue for future research concerns the development of a framework that allows combining symmetry information with other functional or semantic characteristics of digital 3D designs.

Acknowledgements

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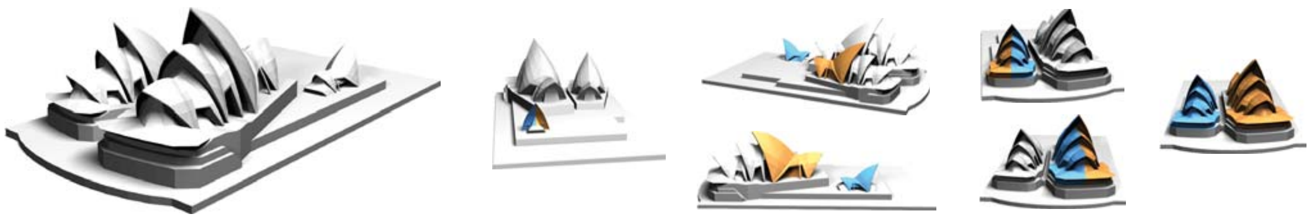

Figure 4: *Large-scale symmetries detected in a digital model of the Sydney opera. The extracted symmetries include reflections, as well as general similarities that involve uniform scaling, rotation, and translation.*

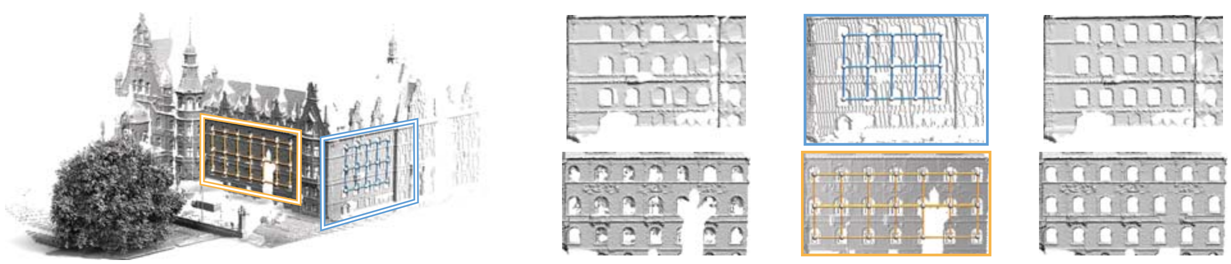

Figure 5: *Structure discovery and model repair on a laser scan of a complex outdoor scene. The algorithm fully automatically discovers two translational grids within the acquired point cloud. Standard surface reconstruction yields an incomplete and inconsistent triangulation shown in the zooms on the left. The models on the right have been created by augmenting the point set using replicated samples from the representative elements prior to reconstruction.*

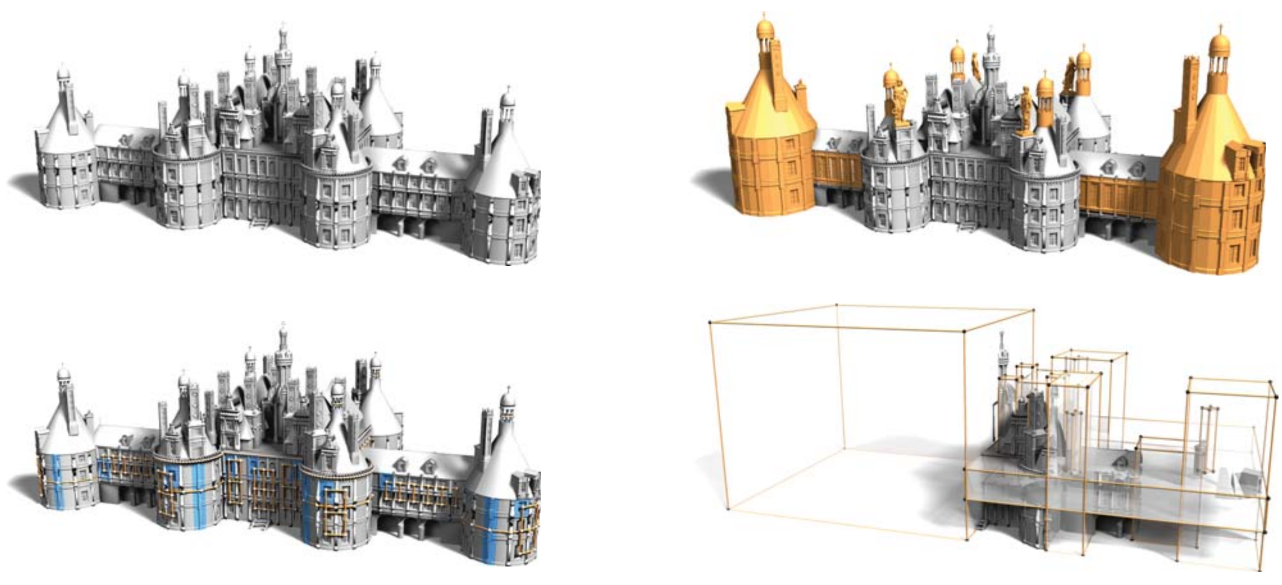

Figure 6: *Conceptual differences between bottom-up structure discovery and top-down symmetry detection. The transparent bounding boxes (lower right) show the extracted symmetry hierarchy that can be utilized for symmetry aware part replacement as shown in the top right. The repetitive translational and rotational structures shown on the lower left support more fine-grain edits to individual structural elements.*

Figure 7: *Structure discovery and procedural modeling on a building facade. The regularity patterns of the model on the left have been extracted automatically and can be modified by the user to alter the facade design as shown in the middle. For comparison, the image on the right shows the original model scaled along the horizontal axis.*

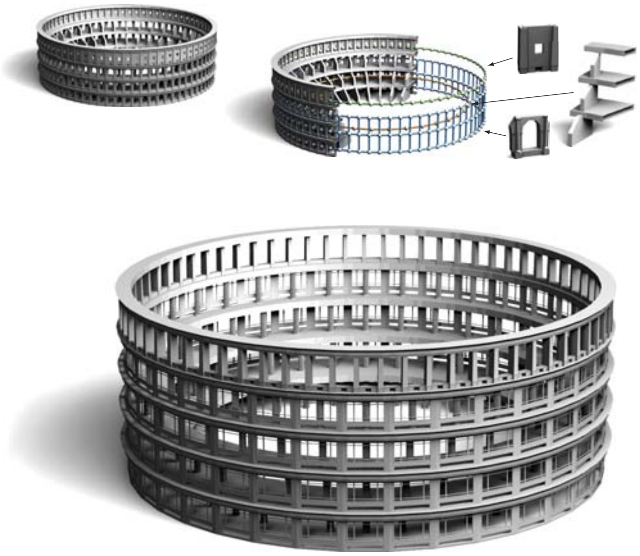

Figure 8: *The input model in the top left corner has been analyzed to reveal three dominant repetitive structures, illustrated in the top right. The zooms show the corresponding structural elements. A new design has been created by modifying the number of repetitions and replacing the repetitive elements with new geometry.*

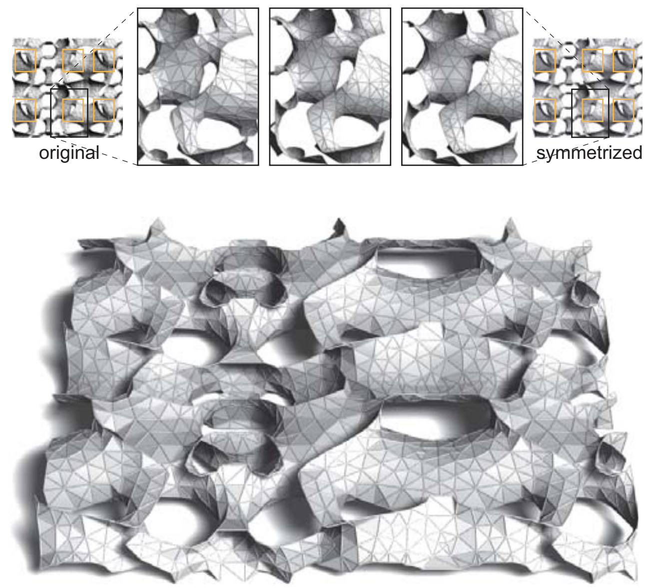

Figure 9: *Symmetrization illustrated on an architectural design study. The top row shows how one of the symmetric elements evolves during the optimization. After processing, the six-fold approximate symmetry of the original model is perfect both in terms of geometry and meshing.*

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Frameworks for practical parametric design in architecture.

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Abstract

This paper is aimed at the development of a theoretical framework that addresses practical applications of parametric design that have been observed in architectural practice. Existing theoretical frameworks are not aimed at addressing this specific use of parametric tools but do provide a set of key themes. Based on these themes a simplified structure is presented here as a means for tackling architectural design development tasks. This is then used in order to examine a case study; the parametric design tasks involved in the design development and documentation of the new Lansdowne Road Stadium in Dublin Ireland. This project was undertaken in collaboration with HOK Sport Architects. The findings from this examination are used to discuss proposals and implications for a practical framework for parametric design in architecture.

Keywords: Parametric; Practice; Theory; Case Study; Lansdowne Road Stadium.

1 Introduction

The potential benefits of parametric tools in practice have been acclaimed while simultaneously acknowledged as increasing in complexity and time required for the design task [Aish and Woodbury 2005]. A survey of recent papers (from conferences such as this) dealing with completed projects demonstrates the increasing popularity of parametric tools in architectural practice. These papers also provide evidence of the potential of parametric tools through descriptions of the process that led to the final product. However the means for arriving at that final process is often not explored, instead descriptions given focus on detailed stages of design and documentation. Published theory concerned with architectural parametric design tasks typically focuses on conceptual design tasks. While observations from practice show that parametric tools are typically being applied to design development problems rather than the early conceptual formulation of the design.

Other design disciplines focusing on application of parametric design to non architectural design tasks provide detailed descriptions of problem solving methodology. Typically these are aimed at problems from a mechanical engineering origin where the goals and means are well defined at the outset. Architectural problems often consist of unknown means and goals and can be described as ill defined tasks or even wicked problems. [Rowe 1987]

While design theories from architecture or other disciplines do not directly relate with observed practical parametric design it is argued that they can form a basis for a theoretical framework for such a task. The aim of this paper is to provide a brief description of a set of key recurring theoretical elements relating to parametric design problem solving. This simplified framework is then used to examine the case study. Where the abstract theory and case study correspond practical examples provide illustration. Where there is no correspondence proposals are made for developing existing theory to apply to parametric architectural design development tasks.

2 Case Study Description

Lansdowne Road site (figure 1) was highly constrained by boundary conditions. These dictated rights-to-light planning restrictions and horizontal expansion limits defining a possible

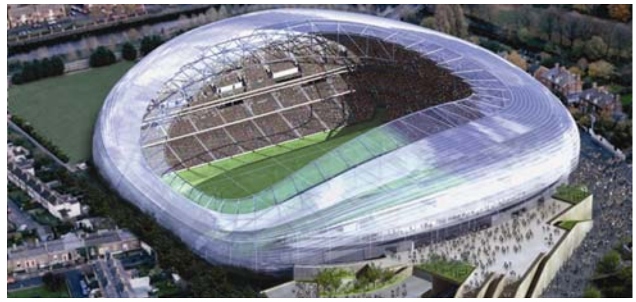

Figure 1: Proposed stadium

volume for development. Internally 50,000 seats and a natural grass pitch were required.

Parametric modeling allowed variations in constraints to be accommodated and then communicated between the architects and engineers. The working method uses parametric technology to define building geometry and to form a dynamic cross-disciplinary link between architectural and structural design at the detailed design phase of a complex project.

The key consideration for the architects was to retain overall geometric control of the stadium. This was achieved by using a combined model, the core component of which was a spreadsheet containing all numeric parameters. This was accessed by a script file that described all geometric rules and relationships for constructing the stadium geometry. This package could then be issued to the engineers. The underlying geometric construction method used an array of similar curved sections arranged radially around the building footprint (figure 2). Variation in these sections was controlled by a set of control curves that mapped the horizontal or vertical change of each of the points defining the section. Each sectional curve defined the centre line key structural roof members.

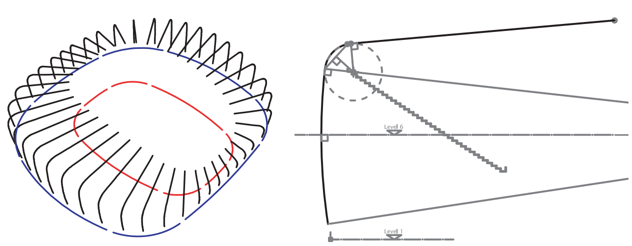

Figure 2: Geometric method.

The structural model developed by the engineers was also parametric, and it used the architectural parametric model as a starting point. Real constraints could be assigned as parameters and used to ensure that the resulting structure was compliant with these rules by definition. Through an interface using Microsoft's

Visual C# programming language, an export routine was written in C# which created a data file for the structural engineering analysis software.

The initial geometric system described above defined centrelines corresponding with the roof structure. For the cladding design solution this definition could be subdivided to define centre lines of a secondary structure to support the cladding panels. A series of initial panelisation studies indicated areas of geometry requiring manipulation to avoid high surface curvature, which would make cladding detailing problematic, and where the local surface gradient was low, which could cause drainage issues. The cladding system consists of a folded polycarbonate profile panel of equal width but varying length, fixed to a standardised bracket system with two axes of rotational freedom (figure 6). These axes of freedom allow the planar panels to follow the stadium geometry.

Panels were detailed with a flexible gasket to allow tolerance as they overlapped the panel below. A third axis of rotation allowing panels to be rotated to any position between 0° (closed) and 90° (open) was defined along the long axis of panels. Air intake and exhaust requirements for air handling units could gradually be incorporated into the façade by feathering the rotational angles of the surrounding panels. Data sheets of all three rotation angles and panel length were produced for construction documentation. For further detail descriptions of this project see [Shepherd and Hudson 2007].

3 Key Themes from Theory

In this section a series of key themes from existing literature are identified and described. It is proposed that these may form a basis for a theoretical framework for practical parametric design. Firstly knowledge, a far reaching theme is introduced, followed by a description of how analysis, synthesis and evaluation apply within this framework. Lastly two further themes are discussed decomposition and representation. The role of this outline framework in the Lansdowne Road stadium project is described in the next section.

3.1. Knowledge

The role of domain or task knowledge (experience or heuristics) is a theme that extends across much of the literature on problem solving and parametric design. Design itself has been defined as a "knowledge based problem solving activity" [Chandraskaran 1990]. While some practice based observations have found that design proceeds in a series of fragmented heuristic episodes [Rowe 1987]. Newell Shaw and Simon [1957] define heuristic as "any principle procedure or other device contributes to the reduction in the search for a satisfactory solution".

More specifically the ways in which knowledge can improve efficiency in design have been identified [Motta and Zdrahal 1996]. Firstly knowledge can be used to reduce the complexity of problems by ruling out ranges of possible solutions. Secondly knowledge of a task can result in identification of key parameters (those having greatest effect on design) from the multiple parameters which may exist. Lastly key parameters have valid ranges that can also be specified through knowledge of the task type.

The starting point in parametric problems will also be influenced by knowledge. The starting state is defined either by choice of an existing solution or similar solution from a similar problem, or by specifying an initial set of parameters. Drawing analogy between the current problem and previous solutions in the designers memory is described as case based [Motta and Zdrahal 1996], case retrieval [Chandraskaran 1990] or recall [Woodbury and Burrows 2006]. The notion of recall has been related to problem analysis and selection of initial "prototype" [Gero 1990] (analytical descriptions of a problem) based on knowledge of a library of previous prototypes. This prototype is then adapted to suit the new problem based on knowledge of the new condition. The prototype includes descriptions of relational, qualitative, computational knowledge and context knowledge.

Once a design has been evaluated it may or may not satisfy constraints and requirements. Through knowledge of the task the designer must either select to try and improve the design or reformulate the problem. If the design is to be improved, a method or operator [Motta and Zdrahal 1996] must be selected and applied in order to fix a design so that it satisfies some constraints. Choice of method or operator is determined by knowledge of the behaviour of the problem. If reformulation is selected (this is common for architectural problems) the analytical stage of the design must be revisited and parameters and constraints adjusted.

The role of knowledge reaches deeply into aspects of parametric design problems. In order to tackle more detailed aspects of work on parametric design it is useful to break design problems into three stages; analysis, synthesis and evaluation. This model of design is discussed in detail by Lawson [2006] where the interdependency between the three stages and iterative shifting between them is stressed.

3.2. Analysis

Gero's [1990] "prototypes" are analytical descriptions of a problem or design task detailing function, behaviour and structure. Functions are a set of requirements that must be transformed into a design. Examples of some functions in the design of a window are the provision of daylight and views while controlling heat loss and noise transmission. Structure relates to the components or elements that will be transformed to produce the design. In the case of the window example the glass, sealants, framing extrusions and hinges. Behaviour concerns the performance of the structure. In the case of window design behaviour would relate to properties such as light and thermal transmission. Providing this analytic description leads to an understanding of behavioural and structural variables or parameters. This type of problem description defines the problem specification [Motta and Zdrahal 1996]. This consists of parameters, value ranges, constraints, requirements, preferences, and global cost function. Valid designs are described as a combination (or set of relationships) of these.

3.3. Synthesis + Evaluation

One broad class of methods for moving towards solutions given the specification of a problem is "propose critique and modify" (PCM) [Chandraskaran 1990]. Within the framework described by Chandraskaran, methods in this class are either based on decomposition – solution - re-composition (DSR), case retrieval or constraint satisfaction. Particular emphasis is given to the DSR process. Once a proposal is established it is verified to ensure satisfaction of functional requirements. The proposal is then critiqued and failures located. Based on the failures the proposal is modified which involves changes to (or adding and removing) requirements, parameters, parameter ranges or constraints. In this way the problem definition can be made more complete.

Motta and Zdrahal [1996] propose a design task structure which fits within the PCM model. This structure involves a set of generic tasks which begin with selection of a starting design. Following this a method for modifying the design is chosen. The choice depends on the completeness of the design and the particular current focus (what specific aspect of design is being addressed). The focus determines the choice of a specific operator selected from a set. This operator is applied and the design evaluated. The new design then forms the starting point for the next iteration.

3.4. Decomposition

While Decomposition Solution Re-composition is a specific method described by Chandrasekaran [1990] the idea of breaking problems into more manageable chunks is a common theme. Jigs or Patterns [Woodbury et al 2007] involve a reduction to the simplest possible description that represents the problem being tackled. This implies abstraction and can also be considered a decomposition task. Each jig is a generic solution to a well described problem. Rowe's [1987] observations in practice found that the design process was unintentionally fragmented suggesting the decomposition task is something that takes place subconsciously. Simon [1996] suggests creative problem solving tasks follow hierarchical structures consisting of assemblies of sub-assemblies which in turn are assemblies of components.

3.5. Representation

Simon [1996] argued the need for consideration of type of problem representation and the need for multiple simultaneous representations. Kilian [2006] agrees but with particular emphasis for designers to reduce their dependency on geometric representation and engage with symbolic diagrams and programmatic descriptions. Woodbury & Burrows [2006] warn of the dangers of too much programmatic focus and argue for intentional and partial representations. By "intentional" Woodbury & Burrows mean that a representation is deliberately about other objects and "partial" because the representation is not a complete description of the design.

4 Task Analysis with Case Study Examples

The Lansdowne Road case study project is considered here as two connected tasks. These are described as envelope and cladding. The envelope task involved production of a model that defined geometric relationships and allowed the control of parameters influencing roof and facade geometry. The cladding task is the development of a cladding solution based on envelope geometry. Details from the development of the two tasks are used to illustrate aspects of the theoretical outline described above.

4.1. Knowledge

Experience from structural engineers of steel façade construction determined that façade geometry should be determined using tangential arcs. This reduced the range of possible types of primitive geometric elements for defining the geometry and also indicated what parameters were needed. The precise descriptions of relationships between geometric elements emerged through development and use of the model. Initially the geometric relationships were judged aesthetically to not deliver enough curvature to sections (figure 3). The relationships were

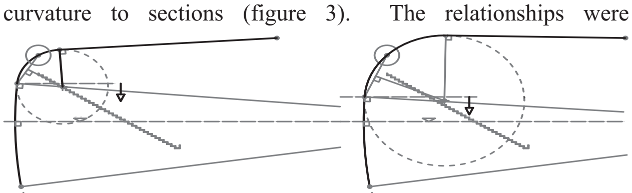

Figure 3: Sectional Curves.

reformulated and new a new parameter added to allow control of section curvature. The valid ranges of this new parameter were discovered through manipulation of the model.

For the envelope a set of starting parameters were roughly defined by a non-parametric model created by the architects as part of the initial design phase. This model was analysed and parameters extracted from this static state were used as the starting point. This was then iteratively refined, knowledge of methods for modification defining choice of operators gradually developed as familiarity with the model increased.

4.2. Analysis

The cladding task demonstrates how the analysis of a problem can develop through experimentation. Initial studies demonstrated the interdependencies between geometry and cladding. Early models indicated rain water run off from panels and also areas of extreme curvature in the envelope geometry. Envelope geometry was modified to reduce concentrations of curvature and ensure rain water direction was not towards the pitch.

Other early cladding studies focused on the setting out methods for panels. These were evaluated on aesthetic and constructability criteria and a preferred solution chosen. As manufacturers and sub contractors became involved, knowledge of the cladding task structure (the choice of components) increased. Panels had to be planar units, this constraint led to the development of a standardised assembly of components (figure 6) (panels, support brackets and a double arm bracket) designed to tolerate the envelope curvature. The knowledge of behaviour of the panels also developed as the task progressed. Each unit could rotate on its axis to provide ventilation to the spaces behind. The process of defining rotation angles while controlling ventilation and preventing wind blown rain is described below.

4.3. Synthesis and Evaluation

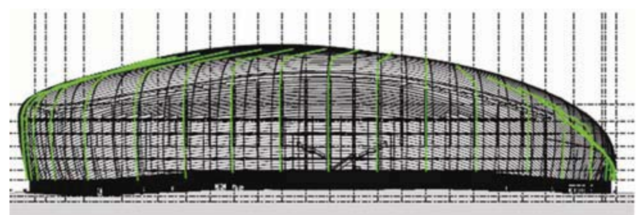

Figure 4: Overlay evaluation.

The initial use of the envelope geometry model illustrates how the PCM method applies here. The starting point described above was iteratively refined using mainly a graphical verification (figure 4). Geometry was extracted at each loop of the process and verified by overlay in 2d as elevations and 3d via viewing in a modeling package. Numeric and graphic data and reporting roof fall angles was also produced. The results of this process resulted in the change in parameters until a satisfactory solution was found. The process of setting the rotational angles for panels on the façade described below provides a detailed example of this kind of synthesis and evaluation combining varied types of representation.

4.4. Decomposition

The case study is already defined as two broad but related tasks; modeling the envelope geometry and the cladding system. Effectively it would have been possible to have these in a combined model and this was the architect's initial goal. As the project moved from the general task of defining the envelope geometry to developing the cladding system there was no need for a single model. Higher level geometry gradually converged on a final state and this formed the starting point for the cladding task. Both the envelope and cladding tasks were further sub-divided. The envelope consists of a series of nine subtasks that involve combining reference geometry with parameters stored in spreadsheets and fusing these two using programmatic scripts to produce the stadium geometry.

4.5. Representation

The models comprise of a varied range of representation the product of both main tasks is a set of geometric objects which are the result of a combining numeric data from excel with rules and relationships defined as a script with a visual two-dimensional graphical control mechanism. The process of setting the rotational angles on the façade provides an example of how representational methods were combined for synthesis and evaluation.

Cladding panels are designed to rotate along their axis to provide air intake and exhaust to and from air handling units located in specific areas on the façade. In the final state they are fixed in position (figure 5). All panels can rotate along axis so units that need to be open can be blended with façade. However if panels not over plant areas are opening, wind blown rain may enter the building. This design problem is a trade off between three conflicting requirements; aesthetic requirement to blend open panels with surrounding panels, the need for openings on the façade sections over plant areas and the need to reduce façade openings over areas not housing plant.

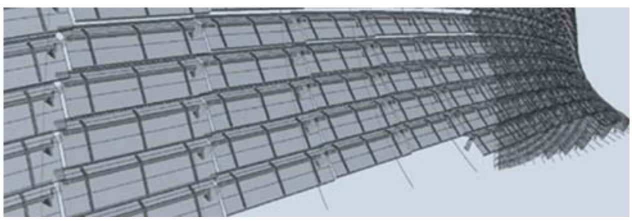

Figure 5: Cladding panels.

An abstracted elevation was created in a spreadsheet each cell represented one panel on the façade (figure 6). A set of initial rotation values were defined. This was used to produce a 3D model that is aesthetically evaluated in a modeling package.

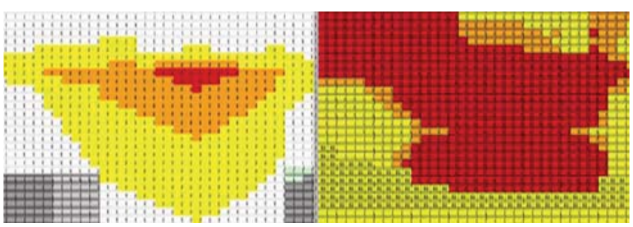

Figure 6: Façade representations.

The ventilating area is measured as the planar area between a panel and the one below. For each panel this value is written to a cell in the spreadsheet (figure 6). Wind blown rain is deemed only to be a problem if the bottom edge of one panel is vertically above the upper edge of the panel below (there is no overlap in elevation). This dimension is also written to cells in the spreadsheet (figure 6). Cells are given a conditional colour scale format to give a visual impression of the results of rotating each panel. In an iterative manner a solution was found through aesthetic evaluation and studying the colour scale mappings generated in the spreadsheet.

5 Conclusion

Much of the reviewed literature suggests a very deliberate and formal process. This was not the case here. The analytic prototypes proposed by Gero [1990] are particularly deliberate where as in this study understanding of the functional, behavioural and structural aspects of the problem came about through working on the problem. This demonstrates that starting with an incomplete description of the problem is possible for this type of parametric design task. This seems to represent an acquisition of knowledge through what has been described as tinkering [Chandraskaran 1990] or exploration [Kilian 2006].

While this type of knowledge grew as the task progressed other types of knowledge had significant impact on the solutions. Aesthetic knowledge or knowing what looks "right" forced certain geometric relationships to be revised and additional parameters to be included. Knowledge of designing cladding systems from both architects and sub contractors informed the definition of new types of component assemblies. Knowledge of the larger scale of production of the curved mullions and constraining the definition of these to arcs greatly reduced the geometric options and therefore reduced the range of possible solutions.

The level to which the process of decomposition solution re-composition applies is deep. Decomposition is either so inherently embedded in this type of task that it does not need mentioning or that it is so crucial, the process deserves more detailed description in relation to architectural design tasks. One aspect of a more detailed handling of decomposition is interdependencies between sub problems.

A highly simplified version of existing theory is presented, this has been used to examine an abridged version of a practical case study. Some of the initial conclusions demonstrate the potential for learning through theoretical reflection on a practical activity in architecture. However the simplification may lead to some misunderstanding and therefore demands a more detailed future study.

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Generating Geometry of Irregular Frameworks Algorithmically

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Abstract

The desire for free form design and therefore the need to design irregular structures can today be viewed in built projects, as well as at architecture schools.

In this paper we will describe a software that was developed in the office of Bollinger und Grohmann. This software can be used for the automatic design of latticed girders or latticed girder grids that are geometrical irregular, but structural effective. While the underlying geometrical parameters are very frugal, the design of complex geometries is possible by this algorithm.

Keywords: Complexity, Algorithmic Generation, Irregular Structures, Optimized Structures, Generative Design

1 Introduction

The usage of conventional methods for the design of structures leads to a high degree of effectiveness and a high degree of regularity. If we try to design irregular structures by traditional approach, we may gain a high degree of irregularity, but it will be hard to reach at the same time certain structural capacities.

To evolve complex structures (non regular structures that have intrinsic load bearing capacities) bottom-up methods seem to be much more appropriate. Hereby it is necessary to regard not only the whole system, but even more the relationship and the interaction of the system's particles.

Modern Hard- and Software allow calculating and evaluating load bearing capacities of almost every structure in short time. It is possible to analyse a great many of alternative solutions of a system and develop optimized systems iteratively. Structures, that feature emergent load bearing capabilities and are not a priori based on a fixed system, can be generated algorithmically.

On this note the author presented in cooperation with Fabian Scheurer (designtoproduction/CAAD, ETH-Zürich) a software [Hofmann et al. 2007], which uses a Genetic Algorithm (GA) for the structural design process. In difference to a GA that did rely typically on global criteria, in this case an algorithm was used, that benefit from fitness values of single elements.

The goal of this research is to generate effective structures automatically, that fulfill at the same time criteria, given by design intent. The emphasis lies not in finding the most suitable optimization process, but to extend the traditional structural design approaches, while implicating the architectural context.

2 Basic Principles

The load bearing capacity of a latticed framework is principally achieved by axial forces. As all joints are by definition pinned connections, moments do not occur. Therefore the quotient of moments and axial forces for each diagonal in a lattice framework is 0. Our assumption was that if we calculate hinge points as rigid joints the quotient still indicates not only the structures fitness, but the fitness of each member. Based on this a lower value indicates a good performance in the system, and a high value indicates, that the member is more stressed by bending moments and therefore not performing well.

3 Generation Process

Based on this, we developed an algorithm that arrays diagonals of a latticed girder iteratively by using this fitness value. For the algorithmic generation we used off-the-shelf software packages, namely structural analysis software and a spreadsheet program. The initial geometry is generated connecting the fixed nodes on the lower and upper chords randomly. (Fig 1) The results of the structural analysis are used by our software to modify the generated elements and evaluate the system again. Modifications only take place to the geometry of the connecting diagonals; the chords, the profile types, materials etc. are fixed. The generation process runs a predefined number of steps.

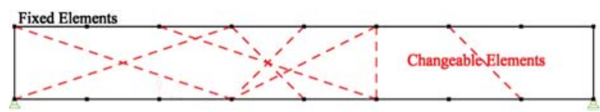

Figure 1: Initial Array of Diagonals

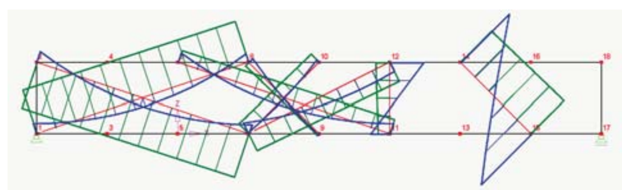

Figure 2: Moments and Axial Forces

In each iteration step the whole structure is calculated. The results from the calculation of each member affect the position of this member in the next iteration step. Members that are selected to change their position perform a random walk along the chords. Members with a low (good) fitness value stay probably on their position.

Furthermore not only the single elements fitness, but maximum deflection of the whole structure is considered to point out the structures overall load bearing capacity. The node with the maximum deflection indicates the systems overall fitness. This value is a precise indicator to compare alternative versions` load bearing capacities.

The following simple rules were used for the behavior of the alterable members:

- the probability to change the position is higher, the higher the fitness value;
- during the generation process the overall chance to move is decreasing;
- during the generation process the maximum distance for each member to move is decreasing;

- a low fitness value of the whole structure increases the number of moving members;
- the best system reached is stored; if after a certain number of steps the systems fitness is not increasing, one or up to all except one member are moved backwards to their stored position;

The probability for diagonals to move depends mainly on their fitness value in relation to the fitness value of the remaining members. For a low fitness the probability to move is low.

All calculations are made under dead load only. Dead load is not a fixed, but a varying value, depending on the sum of the members' length. A light construction will rather implicate a low deflection than a massive one. Small displacement values characterise therefore effective structures.

4 Test Examples

In a testing phase we checked the functionality of this algorithm for simple 2 and 3-dimesional systems. Based on a single-span lattice truss, the regular diagonals are omitted. (Fig 1) So we started with a girder with a quantity of nine nodes at the upper and the lower chord. These nodes are possible connection points for diagonals. To reduce the number of possible solutions, the angle of each diagonal is by definition limited to above 18°. Despite a quantity of about 6^11 solutions is possible. The positions and the angles of the diagonals between the chords are generated by the algorithm.

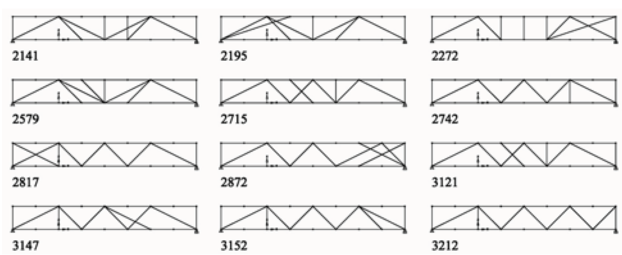

Figure 3: The Last 12 Steps of First Test

For generations with a low number of iterations, systems were evolved that were near to the optimal solution. (Fig 3) If the number of iterations is chosen high enough, the outcome was a traditional lattice girder. (Fig 4)

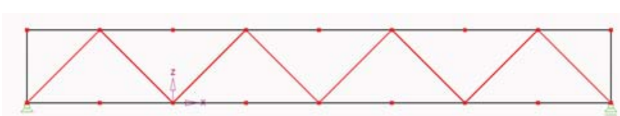

Figure 4: Evolved Conventional Lattice Girder

In the next step we increased the number of nodes of the upper and lower chord and started a new process. The result was an irregular structure that features a lower deflection than the regular latticed girder. (Fig 5)

Figure 5: Irregular Latticed Girder

The gained system is probably not the global optimum in the large solution space, but the comparison with the regular girder shows the principle capacity. Near the supports we have more elements than in the girders center of span; this relates to the occurring moment und the shear forces.

In a last test we changed from a 2-dimesional system into a 3-dimesional latticed girder grid. This structure is supported at four corners. The upper and lower chord follows a rectangular grid, diagonals are freely arrayed between these. Again the found solution possesses a lower deflection than a regular one. (Fig 6) Near the supported corners a concentration of members can be perceived, according to the concentration of lateral forces in this area.

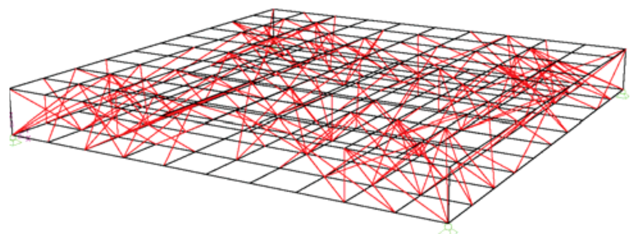

Figure 6: Irregular Latticed Girder Grid

5 Design Examples

5.1. Pedestrian Bridge

The described algorithm was then used for the structural design of a pedestrian bridge by FloSundK architecture. The loads are carried by two girders located at both sides of the footpath. These girders are twisted so their chords describe a hyperbolic paraboloid shell. Supports are located at four positions. As the decline of the diagonals density from one side to another was requested, the number of nodes at which diagonals are attached is also decreasing.

Figure 7: Irregular Latticed Girder

The aim was to find a feasible solution that matches the initial criteria (irregularity and decreasing density), so the generation process was run until a certain capacity was achieved.

Within constrains of the suboptimal twist of the chords the found solution is effective and comparable to a conventionally framework. (Fig 7) This project is currently in implementation

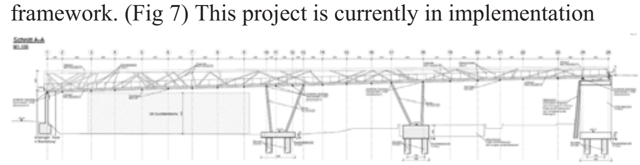

Figure 8: Construction Plan

planning phase and will be probably finished in 2008. (Fig 8)

5.2. Roof of Sports Arena

The Roof of the Rhein-Main Arena in Frankfurt by Coop Himmelb(l)au covers an area of 90 by 120 m. The volume consists of a twisted box. For the roof an upper and a lower girder grid was defined by the architects. These grids are according to the shape of the box twisted to each other. Furthermore the lower grid is folded. (Fig 9)

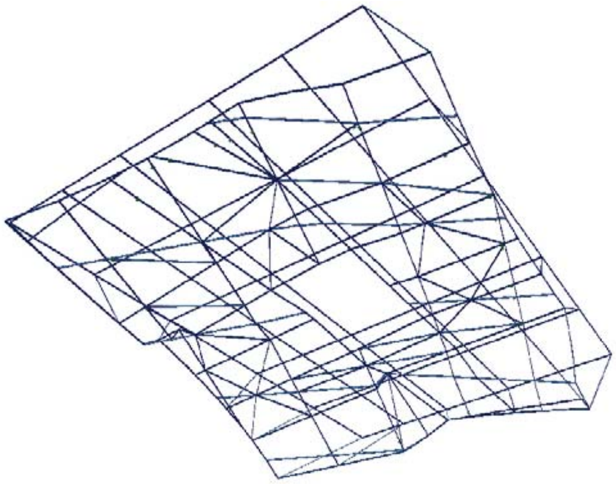

Figure 9: Given Girder Grid

To reach sufficient load bearing capacities, both girders have to be connected to form a space frame. These boundary conditions make it almost impossible to find a regular structure by a engineering approach.

As diagonals are needed not only in the crossing points of the chords, horizontal moments in the chords were taken additional into account.

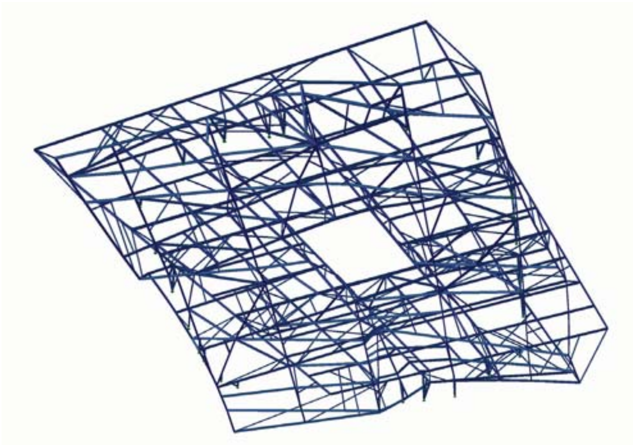

Figure 10: Irregular Latticed Girder Grid

A concentration of members occurs besides the rectangular hole in the middle. A high stiffness of the system was reached, while the weight of the structure was comparable to a regular system. (Fig 10)

Conclusion

As shown in this paper it is possible to design irregular and effective structures using very simple rules and techniques. In our future work it is not only planned to improve functionality and effectiveness of the proposed algorithm, but to extend the geometrical complexity.

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Bitmap-driven Parametric Façades

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Abstract

The design and implementation of bitmap-driven, parametric façades will be examined in a set of different experiments. Beginning with two-dimensional patterns driven by one single parameter, complexity is rising with each further experiment regarding dimensionality and number of parameters. A short overview of current research is given in the conclusion.

Keywords: architecture, façades, parametric design

1 Morphing Tiling Experiment

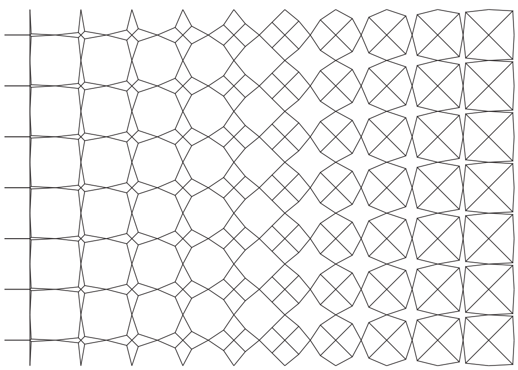

Figure 1: Morphing Tilings, 2005

The experimental setup for the façades presented here is based on an experiment launched in 2005, where self-deforming geometric tiles (Fig. 1, www.counton.org, National Centre for Excellence in the Teaching of Mathematics) were automatically distributed using a simple PERL script in combination with the CAD-Software Vectorworks. Here the degree to which each tile is deformed is steered by the level of brightness of a bitmapped image, where both extremes of deformation are linearly linked with the brightness of the corresponding region of the image (0% to 100%). The position and size of the tile relative to the entire surface defines the region of the bitmap of which the brightness will be sampled. This setup requires that the proportions of the geometry of the surface have to correlate to those of the bitmap.

The geometry of the tiles is archived directly in the PERL script mentioned above. A few representative points of the pattern move along on mathematically defined curves, which generate its deformation. These points are subsequently read in by a conventional CAD program (Fig. 2, Example with Vectorworks) and linked to the resulting patterns, using the script-language provided by the software (e.g. Vectorscript).

Since the two-dimensional tiles in this experiment possess only one single geometric variable, the brightness of each tile was introduced as a second parameter. This project shows that an arbitrary number of parameters can be used from multiple bitmapped images, although the possibilities are limited by the two-dimensionality of the chosen patterns.

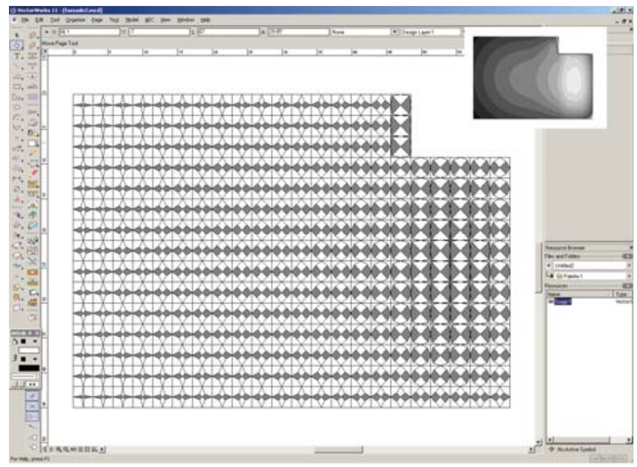

Figure 2: Bitmap-driven Morphing Tilings, 2005

2 Fountainhead

The trials described in Section 1 had already been in preparation for collaboration with KCAP Architects & Planners from Rotterdam, which planned to experiment with a façade for the project "Fountainhead" in Amsterdam. The properties of this façade were to dramatically change over the surface while maintaining a consistent aesthetic. The objective was to be able to react structurally to various inner and outer factors, such as views to the interior, use, or orientation.

For this task the results of the "Morphing Tiling" experiment were expanded by two essential aspects:

2.1. Translation of inner and outer parameters into brightness levels of bitmaps

The geometry of the architectonic volume was determined, and the façade was depicted as a horizontal surface. Afterwards it was determined how the structure should react to each relevant parameter. These connected, often geometric changes in façade elements were assigned a brightness level (0% to 100%) according to their deviation from the norm. These brightness values were then distributed over the façade according to the parameter in question. (Fig. 3, Views to the courtyard, Fountainhead)

Figure 3: Views to the courtyard, Fountainhead, KCAP, 2005

Based on the nature of the parameter and correlating geometric reaction, the relation of the brightness values could either run linearly or erratically.

2.2. Parallel, three-dimensional deformations

Contrary to the two-dimensional patterns referred to in Section 1, real façade elements are multifaceted three-dimensional objects. Their form always carries real, direct consequences in relation to physical attributes, such as exposure to light, views to the interior, acoustical absorption etc. next to design aspects. Moreover the building process involves industrial products subject to production and technical restrictions, which leads to the determination of minimal and maximal sizes of individual building elements.

The number of possible deformations is arbitrarily high, although the so-called boundary values have to be fulfilled in every deformation condition of a façade element. Since these boundary values cannot be verified automatically at this point in time, in practice this often leads to a restriction to a manageable number of parameters that steer the precise form of the elements. (Fig. 4, Sample element Fountainhead)

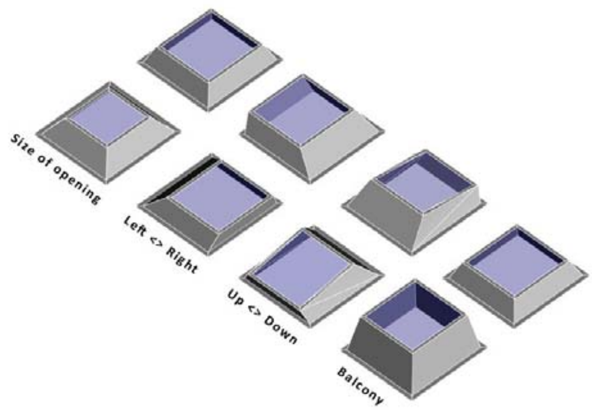

Figure 4: Possible states of a façade element, 2005

The movement of the essential, geometry-deforming points is influenced by several parameters in parallel and no longer on a calculated curve. With two parameters, the possible positions of the points define a surface, with three or more parameters a three-dimensional form. While some movements move independently from one another and therefore occur parallel to each other, others move contrary to each other, in which case the various parameters must be prioritised in order to obtain valid solutions.

2.3. Final Results

A method was developed within the framework of the "Fountainhead" project that allows façade elements to be designed fulfilling various interior and exterior requirements while maintaining a unified aesthetic. In order to achieve this, a geometric skeleton is established, which leads to different, interrelated geometric transformations based on the local parameters of each element. The assignment of an arbitrary high number of parameters is determined by the brightness values of regions of bitmaps whose positions and proportions correspond to those of the element on the façade. In this case, each bitmap controls one single parameter.

The individual element geometries are calculated using a script written in PERL, where the local parameters of each element are taken from the corresponding region on the bitmaps. The output will finally be read in by a conventional CAD program (Fig. 5, Example in FormZ) using the provided script-language of the software. This allows the architects to develop the façade using tools they are familiar with.

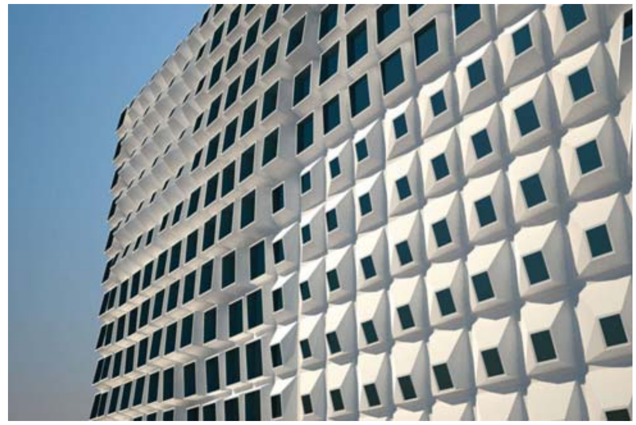

Figure 5: Example façade with 4 parameters, 2005

3 Brave Tailor

In order to instruct the aforementioned method to master students at ETH Zurich, the course "Brave Tailor" was developed. Because one must assume that most architects do not have programming expertise, several modifications of the former procedure were necessary. The goal was that the participants of the course could develop the parameters they wished as well as the resulting deformations of their façade elements as independently as possible.

Although the majority of students have no problem with the generation of a bitmap image, we anticipated that most participants would not be able to grasp the mathematic description of three-dimensional movements in a script language without tedious learning processes. As a result, the question arose as to if CAD software could play a role in the process in order to allow designers to develop their spatial ideas as well as their deformations graphically through abstract parameters. In addition, interfaces were necessary which allow the automatic tiling of the elements according to each parameter as well as the exporting of the generated façade into the CAD programmes normally used by architects.

An evaluation of a number of parametric CAD programmes determined that Digital Project/CATIA by Gehry Technologies fulfilled the specific requirements the best. It is now possible to draw the geometric skeletons of façade elements three-dimensionally and graphically evaluate all of the resulting geometries directly without using script at all. Since all of the essential decisions are now taken outside of the script level, the procedure becomes controllable by the architects:

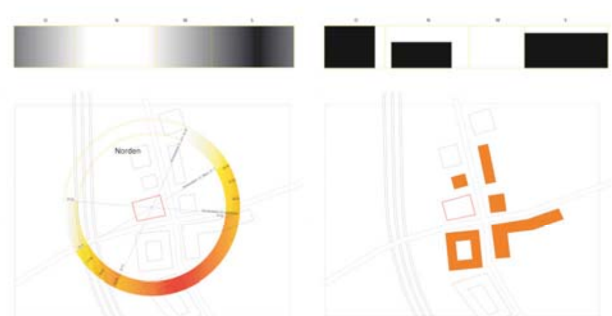

Figure 6: Example Bitmaps, Brave Tailor Course, ETHZ 2006

3.1. Volumes – Unfolding – Parameter

The volume of a building, in the course it was a given one compulsory for all students, is superimposed with an element grid. The unfolding of this volume generates the proportions of the bitmaps through which the parameters will be encoded. These bitmaps can be created in any graphic programme. Finally, they will be read in by a script written in PERL, which orders brightness values from the corresponding region of the bitmap as parameters to the façade elements dependent on their position on the façade. (Fig. 6, Bitmaps from the Brave Tailor course)

3.2. Digital Project/CATIA – parametric 3D element

The designer initially draws the façade element parametrically, in form of a three-dimensional model. As a result, the architect is free to deform individual construction elements in any area, and the allowable movement can be linked in the end to a parameter. This parameter can be set externally at a later point in time through the script, which executes the tiling. As long as the number of bitmaps matches the number of parameters of the CAD model, the bitmaps as well as the CATIA model can be modified without resorting back to the script level. (Fig. 7, Example CATIA model from the Brave Tailor course)

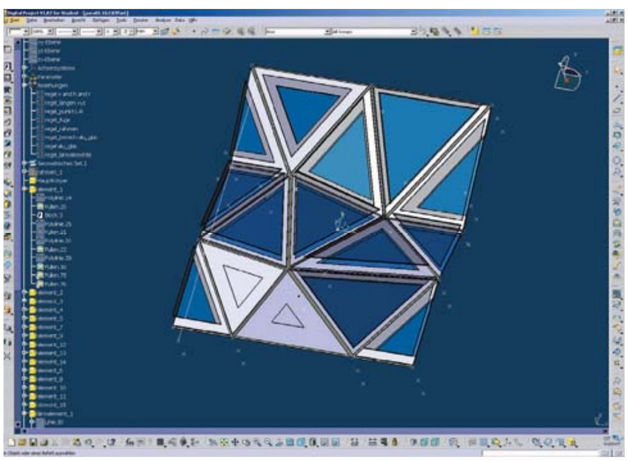

Figure 7: Digital Project Screenshot, Brave Tailor Course 2006

3.3. Generation of the resulting three-dimensional façade

As soon as all parameters are encoded to a bitmap, a script written in PERL maps these parameters to the corresponding elements. The output is read in by a script written in CATIA which tiles the individual façade elements. Since this process requires very large resources depending on the complexity of the 3D model, individual scripts are generated for each surface of the volume. Finally, the complete façade can be exported and developed further with the software of one's choice. (Fig. 8, Results from the Brave Tailor course)

Figure 8: Resulting Façades, Brave Tailor Course 2006

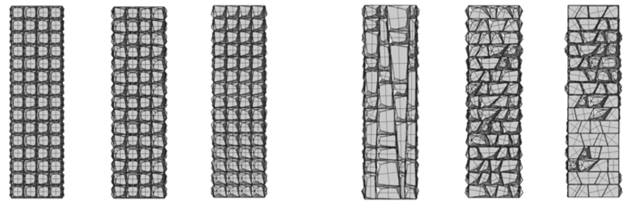

Figure 9: Façade Studies, MAS CAAD 2008

4 Outlook / Conclusion

The "Brave Tailor" course gained very positive feedback from students and teachers and could establish itself in the curriculum. Since the first time it was given in the summer semester 2006, it has been repeated several times and continually improved. The original restriction, which forced one to use orthogonal grids, no longer exists. With the help of a tool written in Rhinoscript, a script language provided by the 3D modeling software Rhinoceros, students can now develop volumes with arbitrary façade divisions and pass on the result in the form of an XML file. A script written in PERL subsequently reads in the XML containing the geometry of the resulting façade elements, identifies the corresponding regions in the bitmaps providing the parameters and finally passes all information to the CATIA based script which is tiling the individual façade elements. (Fig. 9, Example MAS CAAD, 2008). Even though this setup appears more complex than the original one, it turned out that the students had less problems to implement the revised parametric design process, as the unfolding is done in a graphical way instead of an abstract grid described by numbers.

The final technical obstacle is the necessity to install a PERL environment. At the moment, we aim to translate the existing scripts to the now popular script language "Processing", where a graphic user interface will make the procedure accessible to an even larger circle of people.

Figure 10: Hardturm Project, CAAD 2007

In research, parametrically steered façades have proven themselves to be very practical for the detailing of computer-generated architecture. These geometrically often very complex and large volumes already contain most essential interior and exterior parameters in their data models and are therefore ideal for the generation of parametric façade variations. The encoding of parameters in bitmaps is replaced by abstract data exchanged in XML files. This makes the parameters less readable for humans but is necessary as the unfolding of these large and complex volumes is no more straightforward. (Fig. 10, Example Hardturm Project, CAAD 2007 / Fig. 11, Example Research Project, CAAD 2008)

Figure 11: Research Project, CAAD 2008

A number of concepts from the façades presented here have been used for research projects, which investigate the translation of complex designs into façades with parametric elements. Due to the tediousness of real construction processes, none of these projects has been completed at this time, however, it is becoming apparent that here as well, the generation of geometries using scripts should be replaced by their generation using parametric CAD software in the long term in order to be feasible by architects without specialized skills in computers. (Fig. 12, Südpark, HdM & CAAD, 2006-2008)

Figure 12: Südpark, HdM Basel & CAAD, 2006-2008

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Curved Crease Origami

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Abstract

Most origami, both practical and mathematical, uses just straight creases. Curved creases, on the other hand, offer a wealth of new design possibilities. While the first curved-crease models date back to the Bauhaus in the 1930s, curved creasing remains relatively underexplored. The principal challenge considered here is to understand what 3D forms result as natural resting state(s) after folding a set of curved creases, with the potential to enable a new category of design. This problem goes beyond the mathematics of developable surfaces to a question of physics: equilibria of an unstretchable surface with uncreased and creased (plastically deformed) portions folding elastically toward desired angles. Two natural approaches for experimenting with this question are computer simulation and building real models. We follow the latter approach, being more interested in how real materials behave and how the resulting structures might be applied in the field of architecture.

Keywords: architecture, mathematical origami, curved creases, developable surfaces

Figure 1: circles & ellipses; offset

1 Introduction

Most materials used for dry building enclosures are supplied as sheet goods, making developable surfaces—surfaces foldable from a flat sheet—the geometry of choice [She02]. Nondevelopable curved surfaces are made primarily by casting, stamping, or similar methods that need a dye or mold, which lacks economy of scale if the individual components are different from each other.

This research proposes a family of curved three-dimensional geometries that can be fabricated from two-dimensional sheet materials, by way of curved creases; see Figure 1. We also show proofs of concept for fabricating such shapes in materials suitable for architectural applications.

2 Academic Context

The first known reference of curved-crease origami is from a student's work at the Bauhaus, taking a preliminary course in paper study by Josef Albers in 1927–1928 [Win69, p. 434]. Albers later taught the model—formed from creasing a circular piece of paper with concentric circles, alternating mountain and valley—at Black Mountain College circa 1937–1938 [Adl04, p. 33, p. 73]. Irene Schawinsky (wife of Alexander "Xanti" Schawinsky) developed a variation with a central concentric circular hole, exhibited at the Museum of Modern Art (MoMA) in New York [McP44, p. 42]. Later this model entered origami circles through Thoki Yenn from Denmark and Kunihiko Kasahara from Japan. More intricate curved-crease origami sculpture has been designed by Ronald Resch (1970s), David Huffman (1970s–1990s), Jeannine Mosely (2000s), Gregory Epps (2000s), and Demaine and Demaine (2000s); see [DD] for a recent MoMA exhibition and a more detailed history.

The mathematical literature encompasses a reasonable understanding of how curved creases can fold locally; see, for example, Huffman's one paper [Huf76] and the more recent works [FT99, KFC+08]. However, there is essentially no algorithmic understanding of how to design origami using curved creases, unlike the wealth of algorithms for straight creases; see [DO07]. We aim to start filling this gap by experimenting with a range of designs.

Part of the challenge is that the three-dimensional forms taken by curved-crease origami are not usually determined mathematically: treated mechanically, the models have many degrees of freedom. Yet physical paper prefers to rest in one (or a few) stable equilibria. These equilibria (locally) minimize the elastic energy of the system: where paper is uncreased, it tries to return to its original flat state; and where paper has been creased (plastically deformed, effectively modifying its memory), it tries to return to the set crease angle. (Exactly how far the crease-angle memory is set depends on how hard one folds the creases, which affects the final form.) Physics balances these forces, often resulting in surprising three-dimensional forms.

Being difficult to solve analytically, we can find this family of natural folded forms by either physical experiment or computer simulation. Computer simulation of origami [KGK94, MYYT96, BGW06, Tac07, KWC] has so far focused on straight creases, in some cases allowing developable surfaces between straight creases [MYYT96, BGW06] and in one case allowing curved creases [KGK94]; others have tested using piecewise-straight approximations of curved creases [Tac07]. Only a few, however, simulate actual physics of paper [BGW06, KWC]. We opt for an experimental approach both to ground any future computer simulation and to better understand any influence of the material choice (not modeled by these simulators).

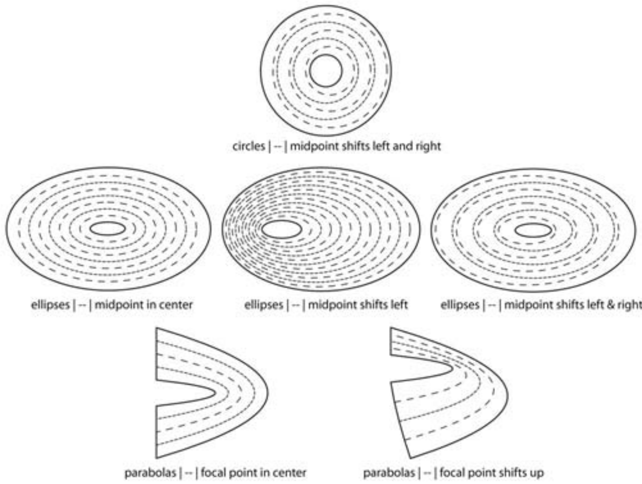

Figure 2a: circles, ellipses, parabolas

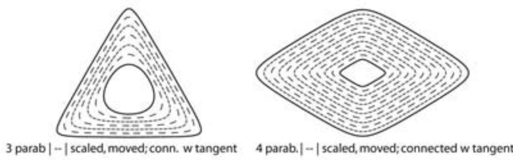

Figure 2b: combined parabolas

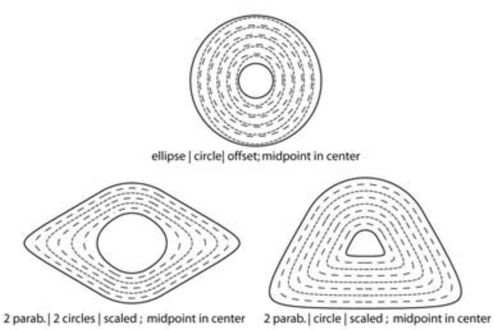

Figure 2c: combined circles, ellipses & parabolas

3 Experiments

We consider curved crease patterns consisting of several regular offsets of a variety of different piecewise-quadratic smooth curves, with fold directions alternating between mountain and valley. In an origami context, such crease patterns correspond to “pleating”, and they naturally extend the Bauhaus form of concentric circles. Specifically, we consider circles, ellipses, and parabolas, both whole and joined together in pieces, mostly to form closed loops. The offsets we consider are concentric, shifting monotonically in one direction, and shifting alternately back and forth in one direction.

Figures 2a–2c show some of the drawn patterns of our experiments. A total of 20 shapes were tested successfully. Only 11 are documented here because of similarities in crease patterns and resulting three-dimensional form. Our experiments use a cotton-based paper, scored on each side with a laser cutter.

Several interesting and sometimes unexpected phenomena arose from our experiments. Perhaps most exciting is the wide variety of three-dimensional forms resulting from sometimes subtly different crease patterns, leaving a broad spectrum for design even within the context of pleating. Also intriguing is that shifting offset ellipses (as well as circles) alternately back and forth along a line, as shown in Figure 3 and 4c, results in a “twisted” folded form that lacks the mirror symmetry of the crease pattern. In contrast, shifting offset ellipses monotonically in one direction results in a mirror-symmetric form, as shown in Figure 4b.

Figure 3: circles; center shifts left and right

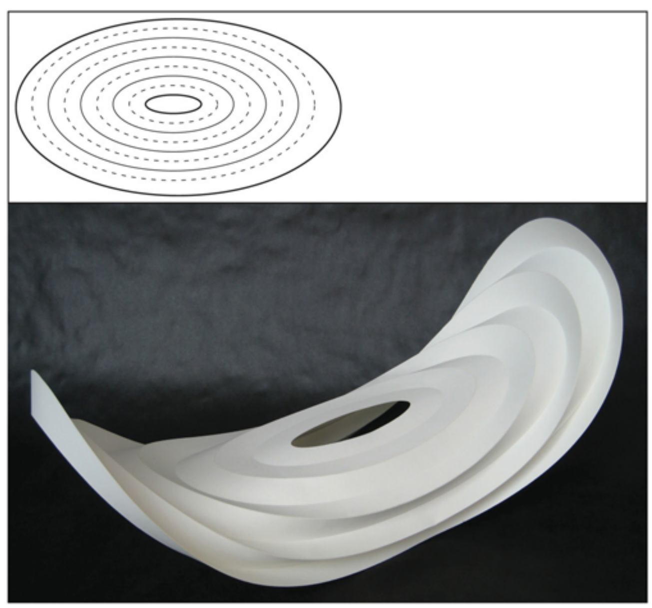

Figure 4a: ellipses; offset on center

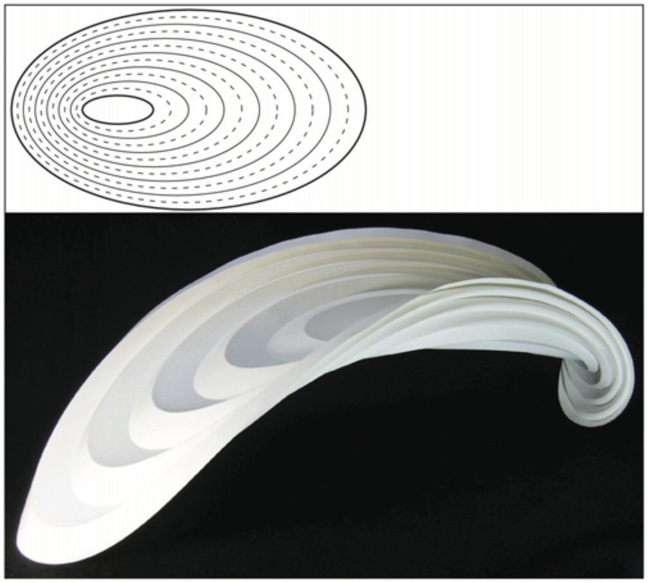

Figure 4b: ellipses; offset, center shifts left

Figure 4c: ellipses; offset, center shifts left and right

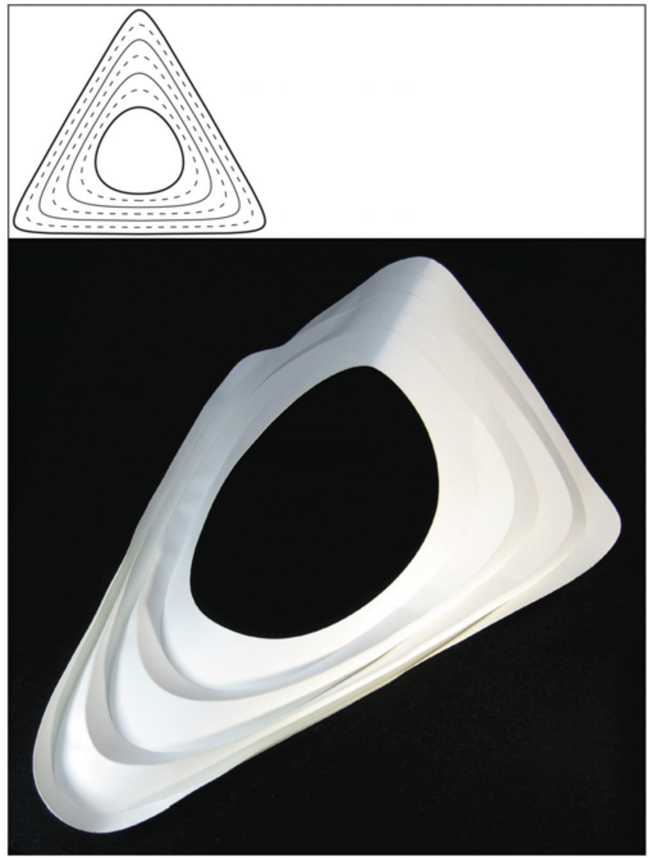

Figure 5: 3 parabolas; scaled, rotated

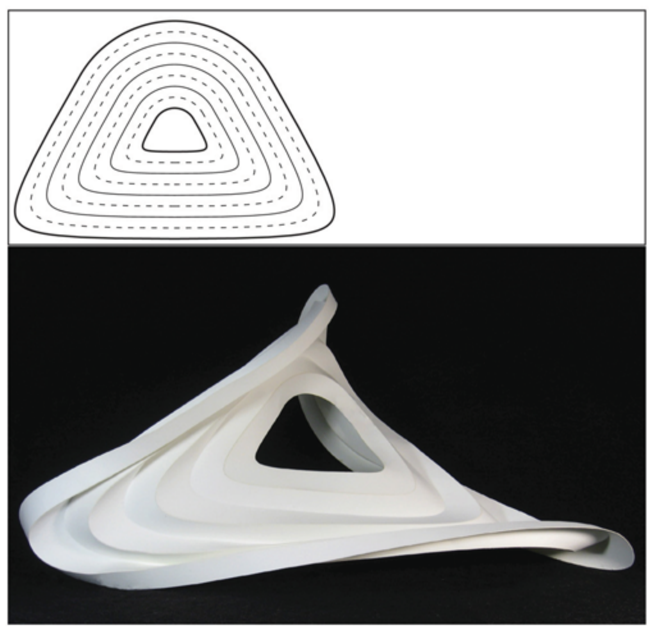

Figure 6: 2 parabolas & circle; scaled; midpt. in center

A more negative example is the combination of three parabolas, shown in Figure 5, where it appears impossible to fold along all creases by a positive amount in the desired direction, resulting in a flat area. This outcome is not surprising, given the close proximity to a straight-crease design of concentric triangles, which behaves similarly. More interesting is that the closely related model shown in Figure 6, with two parabolas and a somewhat larger circular segment, folds nicely into a three-dimensional form with precisely the desired creases.

4 Industry Context: Proof of Concept

The second part of this research is to investigate manufacturing techniques within an industry context, as related to the fabrication of architectural elements. We produced several prototypes for proof of concept and Figure 7 documents the successful ones. The goal is to create a direct connection from mathematical origami to fabrication technology relevant to architecture today.

The challenge regarding an architectural implementation is to find elastic materials that fold into these natural shapes, without showing additional creases, while being suitable for exterior applications. The proposed fabrication method is based on perforations, because a series of small holes can act as a guide for bending. S-shaped dashes for these perforations help metals bend easily [Ori]. Our successful experiments shown in Figure 7 were made of polycarbonate and steel cut with a water jet. This method also seems very promising for thicker sheets of aluminum.

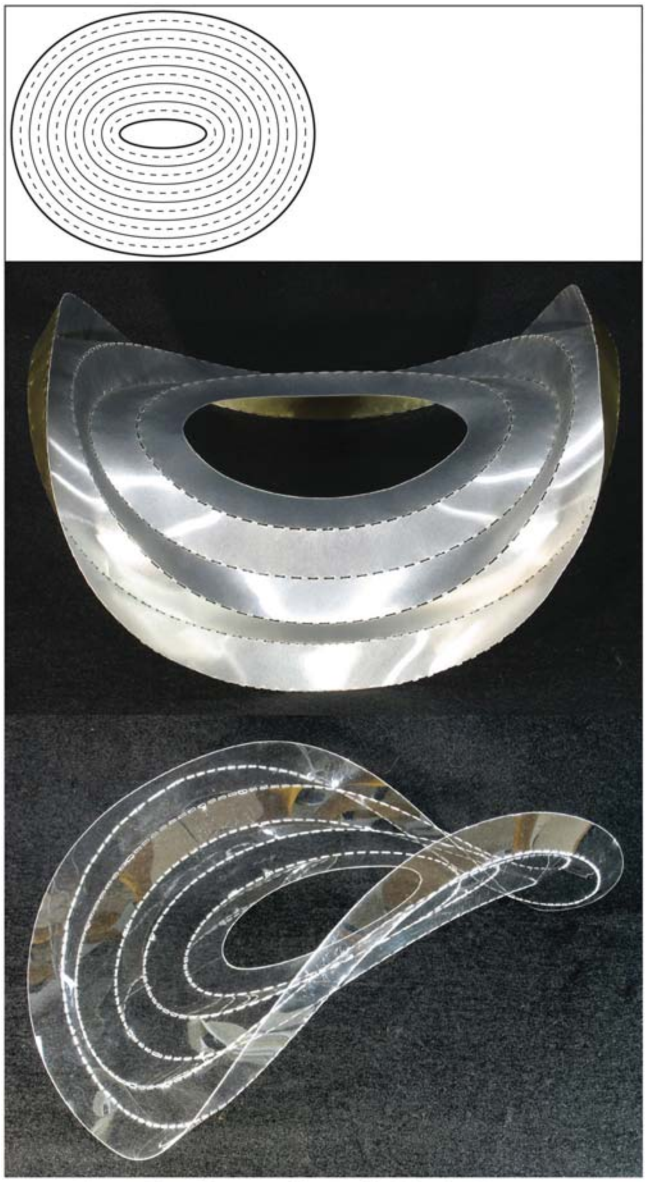

Figure 7: ellipses; offest w/ midpoint in center metal & polycarbonate

Conclusion

This experimental research aims to elucidate the relationship between curved crease patterns and the natural three-dimensional forms that result. As little is known about this relationship, our trial-and-error approach may help indicate interesting behaviors that can be exploited in a more general algorithmic approach.

Creating three-dimensional shapes out of flat sheet goods has inherent architectural advantages and will contribute to the field by providing form generation techniques for developable surfaces. We find this area ripe for further collaboration between mathematics, architecture, design, and fabrication.

Acknowledgments

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Developable Surfaces with Curved Creases

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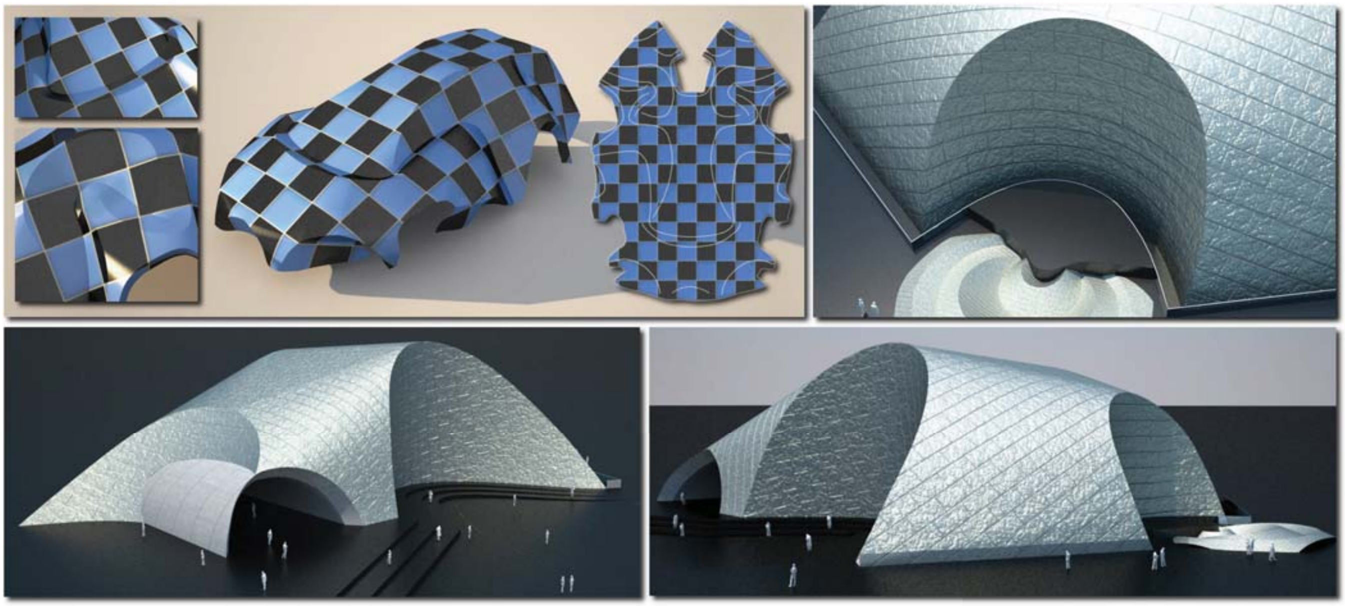

Figure 1: *Top left: Reconstruction of a car model based on a felt design by Gregory Epps. Close-ups of the hood and the rear wheelhouse are shown on the left. The fold lines are highlighted on the car's development. Top right and bottom: Architectural design. All shown surfaces can be isometrically unfolded into the plane without cutting along edges and can thus be texture mapped without any seams or distortions.*

Abstract

Fascinating and elegant shapes may be folded from a single planar sheet of material without stretching, tearing or cutting, if one incorporates curved folds into the design. We present an optimization-based computational framework for design and digital reconstruction of surfaces which can be produced by curved folding. Our work not only contributes to applications in architecture and industrial design, but it also provides a new way to study the complex and largely unexplored phenomena arising in curved folding.

Keywords: curved fold, developable surface, computational origami, architectural geometry, industrial design.

1 Introduction

This paper is an excerpt from [Kilian et al. 2008]. More details on curved folding can be found in the aforementioned paper.

Developable surfaces appear naturally when spatial objects are formed from planar sheets of material without stretching or tearing. Paper models such as origami art are prominent examples. The striking elegance of models folded from paper, such as those by David Huffman [Wertheim 2004], arises particularly from creases known as *curved folds* (see Figure 2). Such folds can be generated from a single planar sheet. Early investigations of curved folds are due to Huffman [1976]. More recently, computational geometers became interested in folding problems and computational origami [Demaine and O'Rourke 2007]. Their work concentrates on piecewise linear structures; according to [Demaine and O'Rourke 2007], 'little is known' in the curved case. While industrial designers have started to explore the technique of curved folding (www.robofold.com), current geometric modeling systems still lack any support for such a design process (in fact, most CAD systems are lacking a proper treatment of developable surfaces). As a result, Frank O. Gehry, who favors developable shapes for many of his architectural designs (cf. [Shelden 2002]), has initiated the development of a CAD module for developable surfaces by his technology company. To the best of our knowledge, curved folding is not present in that module either.

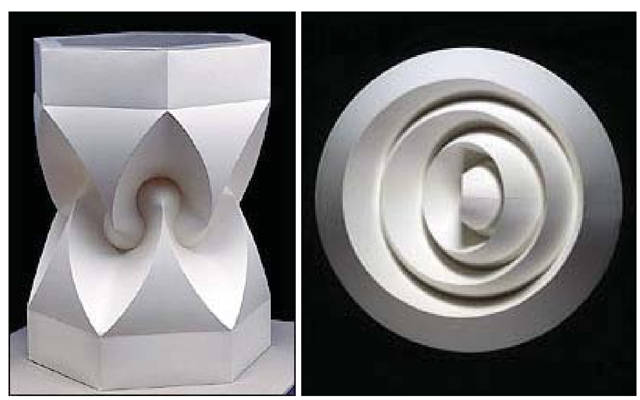

Figure 2: *Two examples of paper models featuring curved folds that were created by David Huffman.*

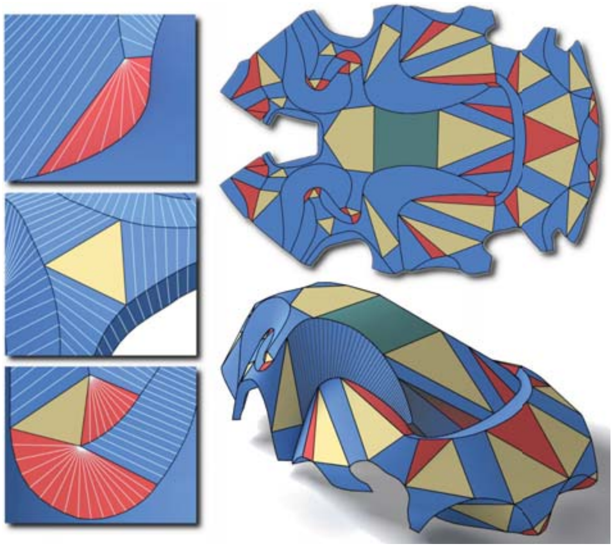

Figure 3: *The car model of Figure 1 and its development (top right). The patch decomposition into torsal ruled surfaces is shown using the following color scheme: planes are shown in yellow, cylinders in green, cones in red, and tangent surfaces in blue. Sample rulings are shown on some patches of the windshield and the side window. Such a segmentation is essential for NURBS surface fitting and manufacturing.*

Motivated by the potential and interest in the use of curved folding for various geometric design purposes, we investigate this topic from the perspective of geometric modeling. Developable surfaces are well studied in differential geometry [do Carmo 1976]. They are surfaces which can be unfolded into the plane while preserving the length of all curves on the surface. Developable surfaces are composed of planar patches and patches of ruled surfaces with the special property that all points of a ruling have the same tangent plane. Such *torsal ruled surfaces* consist of pieces of cylinders, cones, and tangent surfaces, i.e., their rulings are either parallel, pass through a common point, or are tangent to a curve (*curve of regression*), respectively. Whereas a torsal ruled surface has only one continuous family of rulings, general smooth developable surfaces are usually a much more complicated combination of patches. The presence of planar parts is the main source of this huge variety of possibilities. The level of difficulty is further increased if one admits creases, i.e., curved folds (see Figure 3).

2 Discrete developable surfaces

Developable surfaces. As our basic representation of developable surfaces we employ quad-dominant meshes with planar faces, which is also the representation of choice for discrete differential geometry [Sauer 1970; Bobenko and Suris 2005].

A strip of planar quadrilaterals (Figure 4, left) is a discrete model of a torsal ruled surface. Such a 'PQ strip' can be trivially unfolded into the plane without distortions. The edges where successive quads join together give us the discrete rulings. In general they form the edge lines of the regression polyline $\mathbf{r}_0, \mathbf{r}_1, \ldots$; in special cases the discrete rulings are parallel, or pass through a fixed point. A refinement process which maintains planarity of quads generates, in the limit, a torsal ruled surface Σ (Figure 4, right). Its rulings are the limits of the discrete rulings, which in general are tangent to the regression curve $\mathbf{r}(t)$, and in special cases are parallel (cylinder), or pass through a fixed point (cone).

The representation of developable surfaces as PQ strips provides various advantages over triangle meshes: (i) developability is guaranteed by planarity of faces and the development is easily obtained, (ii) subdivision applied to PQ strips provides a simple and computationally efficient multi-scale approach [Liu et al. 2006], (iii) the regression curve – which is singular on the surface and thus needs to be controlled – is present in a discrete form, and (iv) the curvature behavior can be easily estimated as shown in [Kilian et al. 2008].

Curved folds. In the smooth setting, the following fact about curved folds is well known (see e.g. [Huffman 1976]): At each point of a fold curve c, the osculating plane of c is a bisecting plane of the tangent planes on either side of the fold. This follows immediately from the identical geodesic curvatures of the fold curve c with respect to the two adjacent developable surfaces S_1 and S_2. Hence, given the surface on one side of a fold curve, we can compute (part of) the other as the envelope of planes, obtained by reflecting the tangent planes about the osculating planes of c. This is discussed in some detail in [Pottmann and Wallner 2001], but one finds only that part of S_2 whose rulings meet c. Thus, the approach is not sufficient for most of our tasks where, in addition, multiple folds may appear, and the locations of such fold curves only become known in the process of optimization. In contrast to the smooth setting, in the discrete case there are more degrees of freedom in choosing the surface S_2. This fact necessitates an optimization approach as described next.

3 The basic optimization algorithm

The basic optimization algorithm *simultaneously* optimizes a discrete developable surface M and its planar development P. To maintain isometry between corresponding faces of M and P, we originally let M be a quad-dominant soup of planar polygons M^i in space. These polygons are isometric to the corresponding faces P^i in the planar mesh P, see Figures 5 and 6. During the optimization, the polygon soup M will become a mesh via a registration procedure which bears some similarity to that used in the PRIMO mesh deformation tool [Botsch et al. 2006]. However, our optimization requires more sophistication since we have to simultaneously optimize the development P while satisfying various other constraints.

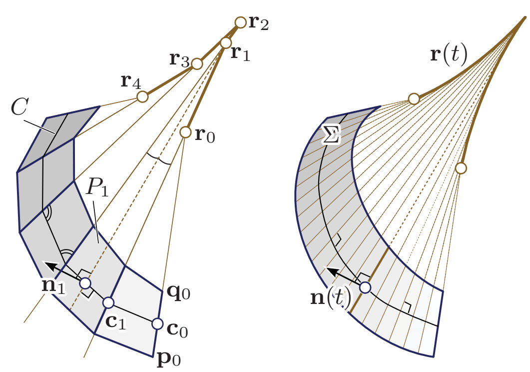

Figure 4: *A PQ strip (left) is a discrete model of a developable surface Σ (right). The intersections of edges $\mathbf{p}_i\mathbf{q}_i$ of adjacent planar quads generate the regression polyline $\mathbf{r}_i$. In the limit of a refinement process, this regression polyline becomes the regression curve $\mathbf{r}(t)$. Polylines C, whose edges $\mathbf{c}_i\mathbf{c}_{i+1}$ intersect inner bisectors of consecutive discrete rulings at right angles, are discrete versions of principal curvature lines, and serve for the definition of discrete curvatures. The unit normals to planar quads P_i are denoted by $\mathbf{n}_i$.*

Optimization starts with an initial set of pairs (M^i, P^i) of isometric planar polygons (primarily quads in our setting). The faces P^i form a planar mesh P, while in space the corresponding polygons M^i are assumed to roughly represent a developable shape D. They are not yet precisely aligned along edges. Thus M is not a mesh but a polygon soup. See [Kilian et al. 2008] on how to compute initial positions P^i for different applications.

The unknowns. We introduce a Cartesian coordinate system in the plane of P, with origin $\mathbf{o}$ and basis vectors $\mathbf{e}_1, \mathbf{e}_2$. Each face P^i of P is congruent to the respective face M^i in space. For each such face, the image of $(\mathbf{o}; \mathbf{e}_1, \mathbf{e}_2)$ under the isometric transformation $P^i \mapsto M^i$ is a Cartesian frame $(\mathbf{o}^i, \mathbf{e}_1^i, \mathbf{e}_2^i)$ in the plane of the face M^i. If (p_x, p_y) are the coordinates of a vertex $\mathbf{p}$ of P^i, then the corresponding vertex $\mathbf{m}$ of M^i is $\mathbf{m} = \mathbf{o}^i + p_x\mathbf{e}_1^i + p_y\mathbf{e}_2^i$. During the optimization, the frames $(\mathbf{o}^i, \mathbf{e}_1^i, \mathbf{e}_2^i)$ undergo a spatial motion, and the coordinates (p_x, p_y) can also vary since we allow the polygons P^i to change.

We linearize the spatial motion of any face M^i using an instantaneous velocity vector field: The velocity of a point $\mathbf{x}$ can be represented as $\mathbf{v}(\mathbf{x}) := \bar{\mathbf{c}}^i + \mathbf{c}^i \times \mathbf{x}$, where $\bar{\mathbf{c}}^i, \mathbf{c}^i$ are vectors in 3-space. Thus a vertex $\mathbf{m}_+$ of the displaced quad face is given by:

$$\mathbf{m}_+ = \mathbf{m} + \bar{\mathbf{c}}^i + \mathbf{c}^i \times \mathbf{o}^i + p_x(\mathbf{c}^i \times \mathbf{e}_1^i) + p_y(\mathbf{c}^i \times \mathbf{e}_2^i).$$

The new vertex position is linear in the unknown parameters $\bar{\mathbf{c}}^i, \mathbf{c}^i \in \mathbb{R}^3$ of the velocity field, and also linear in the unknown coordinates p_x, p_y. We optimize over *both* the velocity parameters and the coordinates. The products $p_x\mathbf{c}^i$ and $p_y\mathbf{c}^i$ result in nonlinear terms if we insist on simultaneously optimizing them. To avoid nonlinear optimization, we alternately optimize for displacements $\bar{\mathbf{c}}^i$, $\mathbf{c}^i$ and for vertex coordinates p_x, p_y. Since our objective function is quadratic in both types of unknowns this amounts to alternately solving two sparse systems of linear equations.

Applying displacements corresponding to $\mathbf{c}$, $\bar{\mathbf{c}}$ destroys the exact isometric relation between corresponding faces P_i and M_i. It is therefore necessary to further modify the vertices of M^i. This can either be done by rigid registration of the face P^i to the estimated vertex locations $\mathbf{m}_+^j$ as proposed by Botsch et al. [2006], or by using a helical motion as described in [Pottmann et al. 2006] – we use the former approach.

The objective function. Our objective function is designed to simultaneously ensure that M becomes a mesh, fits the input data, and satisfies the aesthetic requirements of the application.

If a vertex $\mathbf{p}$ in the planar mesh P is shared by k faces, then $\mathbf{p}$ corresponds to k different vertices $\mathbf{m}^1, \ldots, \mathbf{m}^k$ of the corresponding k faces in M. Since these vertices should agree in the final mesh, we use a *vertex agreement term* of the form:

$$F_{\text{vert}} := \sum (\mathbf{m}_+^i - \mathbf{m}_+^j)^2,$$

where the sum extends over all $\binom{k}{2}$ combinations per vertex $\mathbf{p} \in P$, and over all vertices in P.

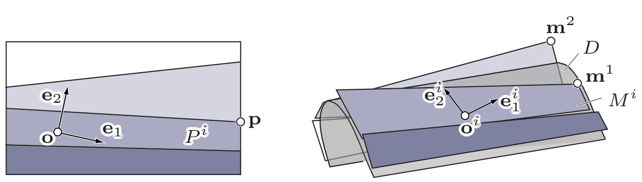

Figure 5: *Basic setup for the optimization when a reference surface D is used. Faces with the same color are congruent.*

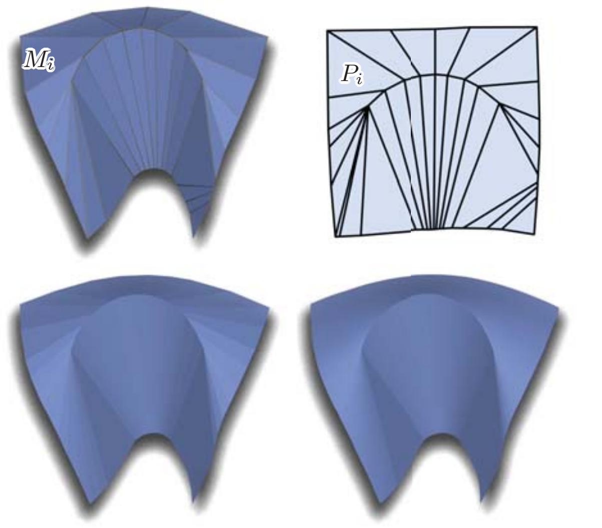

Figure 6: *Top left: Initial polygon soup M. Top right: Development P. Bottom left: M after subdivision and optimization. Bottom right: M after three rounds of subdivision and optimization.*

For M to approximate an underlying data surface D, we include a *fitting term* F_{fit} which is quadratic in the vertex coordinates $\mathbf{m}$. Let $\mathbf{m}_c$ denote the closest point in D to $\mathbf{m}$, and let $\mathbf{n}_c$ denote the unit normal at $\mathbf{m}_c$ to the underlying surface. We use a linear combination of the squared distance $(\mathbf{m} - \mathbf{m}_c)^2$ and the squared distance to the tangent plane $[(\mathbf{m} - \mathbf{m}_c) \cdot \mathbf{n}_c]^2$ as the data fitting term. When fitting curves, especially near boundaries, we use tangent lines instead of tangent planes.

Finally, we need a *fairness term* F_{fair}. For each pair of adjacent quads M^i and M^j of the PQ strip, we use the discrete bending energy $w_{ij}(\mathbf{n}_+^i - \mathbf{n}_+^j)^2$ of the corresponding developable surface as described in [Kilian et al. 2008] as the fairness term. The normal of a quad M^i of M is given by $\mathbf{n}^i = \mathbf{e}_1^i \times \mathbf{e}_2^i$. Under small displacements, this normal linearly varies as $\mathbf{n}_+^i = \mathbf{n}^i + \mathbf{c}^i \times \mathbf{n}^i$. Given a polyline $(\mathbf{p}_1, \ldots \mathbf{p}_n)$ representing a fold line, i.e., a crease or a segment of a boundary curve, the contribution to F_{fair} is a sum of squared second differences $\sum(\mathbf{p}_{i-1} - 2\mathbf{p}_i + \mathbf{p}_{i+1})^2$. Fairness terms are also applied to the respective polylines in the planar domain P.

The fairness term F_{fair} alone is not always sufficient to maintain convex quads, and to prevent flips in the planar mesh P, especially when the quads become thin after several steps of subdivision. Hence we add another term F_{conv} to enforce convexity. We assume that the orientation of each face of P coincides with the orientation of the plane induced by the frame $(\mathbf{o}; \mathbf{e}_1, \mathbf{e}_2)$. A corner $(\mathbf{p}_{i-1}, \mathbf{p}_i, \mathbf{p}_{i+1})$ of a planar polygon is convex if and only if the oriented area of the triangle $\Delta(\mathbf{p}_{i-1}, \mathbf{p}_i, \mathbf{p}_{i+1})$ is positive. This term also prevents flipping of faces.

The algorithm. Combining all individual terms, our basic optimization problem reads

$$\begin{aligned} &\text{minimize} && F = F_{\text{vert}} + \lambda F_{\text{fit}} + \mu F_{\text{fair}} \\ &\text{subject to} && F_{\text{conv}} \geq 0. \end{aligned} \tag{1}$$

We alternately minimize the objective function over new positions of vertices in P, and displacements of faces in space, i.e., velocity vectors for the corresponding face planes. Note that the weights w_{ij} (see [Kilian et al. 2008]) of F_{fair}, which only depend on the planar mesh P, remain fixed when optimizing for displacements of faces

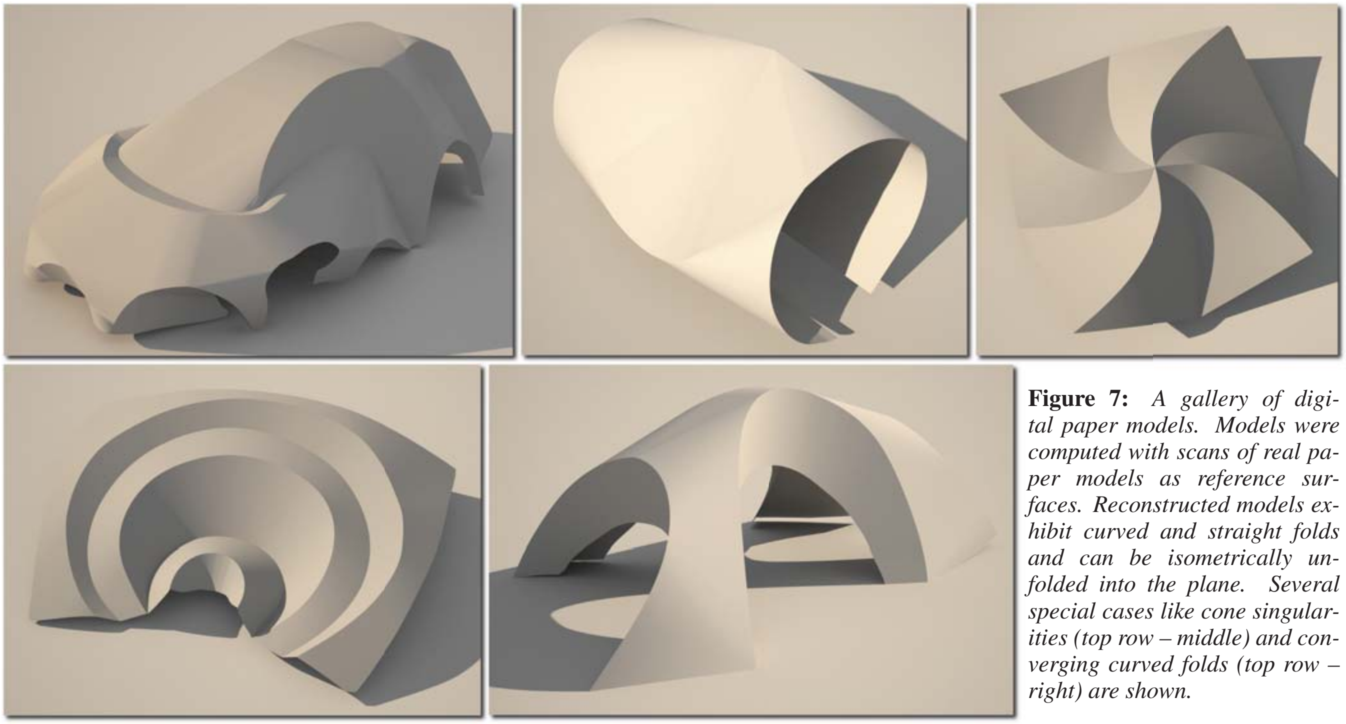

Figure 7: *A gallery of digital paper models. Models were computed with scans of real paper models as reference surfaces. Reconstructed models exhibit curved and straight folds and can be isometrically unfolded into the plane. Several special cases like cone singularities (top row – middle) and converging curved folds (top row – right) are shown.*

in space and the side condition F_{conv} is also not needed. Hence, the spatial sub-problem amounts to solving a sparse linear system, and subsequent application of the corresponding rigid body motion per face. Optimizing the development P is more involved since the weights w_{ij} change in a non linear way as the geometry of P changes. Additionally we have a quadratic term F_{conv} to maintain convexity as a side constraint. With the meshes scaled to fit inside a unit cube, we found $\lambda = 1$ and $\mu = 10^{-4}$ to be good values to start the optimization.

Given an initial mesh P and a polygon soup M that roughly approximates a developable shape, we alternately optimize for P and M. The optimization terminates when the vertex agreement term falls below a given threshold. For the next refinement level, we subdivide the current mesh P, and map the new faces to space using the rigid transformation associated with the faces of P at the current level. The refinement process splits each quad of P to form two new ones. Splitting is performed along the edges that do not correspond to ruling directions (see Figure 4, right). The process is repeated until desired accuracy is reached.

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Design By Tool Design

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Abstract

The Text is a plea to practice design with one‘s own designed tools: *to design by tool design*.

It includes an empiric survey of the influence of self-made design tools on the developing process of design ideas. The description of series of experiments in which self-made design tools have been created and applied, using the programming language Logo.

Keywords: architecture, design process, design tools, self-made tools, Logo

1. Introduction

Without a doubt currently available software solutions used for construction and modeling, with their possibilities and constraints, formally shape the products developed with them. It is difficult today to buy a toaster that doesn't boast a bulging body, which to any insider displays the obvious geometry of nurbs-surfaces.

To what extent, then, have the developers of software packages and their digital tools assumed the function of authors of the products developed with that software? Is the user working with said software still a "designer" or has he merely become an "implementer" of the formal ideas of the expert software developer?

Of equal interest is the question to what extent the daily use of these software packages decisively shapes the development of design ideas—in the sense that the options provided by the digital tools are slowly seen as the only possible solutions of the design problem. Which architect will design a stair that cannot be found in the parametric design library of his software? To what extent are his ideas of stairs already determined, in a limiting sense, by the enticing options found in this repertoire?

Suppose that we are not only interested in developing design ideas but in the *process* of developing design ideas. Suppose we believe that thinking about the processes of developing design ideas is an integral part of the process of design itself. What could be awarded a practice of designing that is aware of the interferences and influences of tools to deliberately use this as a benefit? This paper aims to provide an initial response.

2. Starting point

Starting point are observations and experiences of my professional practice as an architect and as a teacher in the field of architecture and design. The following is a series of case studies, pointing out several issues which do matter in the design process of an architect or any other designer.

3. The case studies

Regarding the following cases we provide these questions:

- What is the role of the tools used in the specific design?
- To what extent are the tools used formative regarding the characteristics of the product?
- Does the tool act more in the function of a *transporter* of an idea or more in the function of a *generator* of an idea?
- To what extent might the authorship of products be considered to be affected by the tools used?

The emphasized tools are regarded to have exemplary relevance in the tasks of the design process.

3.1. Minehead

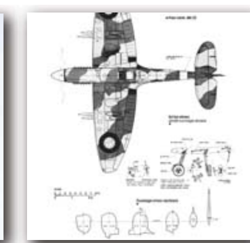
Tool: Latthammer

B. + H. Becher, *Fördertürme*, 1985

Anonymous architecture, construction of a tower with the simplest means, without blueprint: shelves hammered together. Very functional, significant. The tool acts as a transporter of the raw idea of a minehead, despite its limitations. It *shapes* the formal properties of the product.

3.2. Spitfire

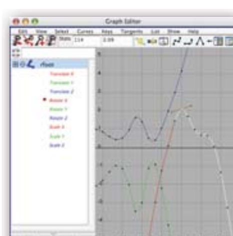
Tool to draw an ellipse



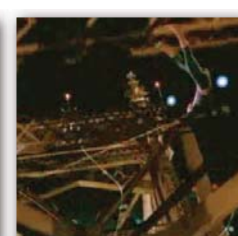
Supermarine Spitfire 1938

All cross-sections and outlines of this aircraft are composed of parts of elliptic curves. Deliberate restriction to a specific geometric method of construction. The tool is chosen to achieve a highly homogenous shape. In contrast to the previous case the *choice of the tool* is part of the design process.

3.3. Spider-Man



Tool: Graph Editor, *Maya* 2008



Spider-Man, Sam Raimi 2002

The figure of *Spider-Man* swings in the silk threads of a spider in a stunning move along the truss of a bridge. This movement may be inspired by the way a rubber ball bounces around inside a small room. But in its peculiar way, it is unthinkable, unimaginable without the knowledge of the potential of the tools of high end animation software such as *Maya*. Here the tool might be considered as the *generator* of an idea, the movement of a specific character, a creation. We assume the designer did not make experiments with flying rubber balls, but fiddled around with software tools.

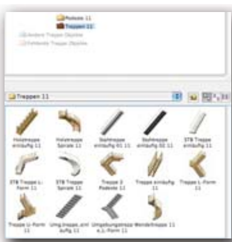
3.4. Heaven

Tool: Background image library, *ArchiCAD 11*

Google image search "rendering"

A search on the internet for images with the word "rendering" in the name reveals a great number of visualisations of buildings under bright blue skies with white clouds. Surprisingly, some of them resemble each other strongly. In some cases the tool used is the *ArchiCAD* background image library, the image "heaven_clouds.jpg". The tool is capable of lightening up any architecture with the brightest investor optimism. It adds *content* to the design.

3.5. Stairmaker

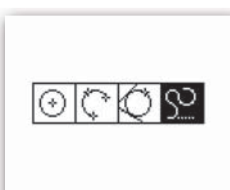


Tool: *Stairmaker* library, *ArchiCAD 11*

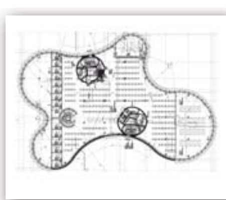
Stair No. 10

State of the art architectural CAD software allows the user to work with data-enhanced parametric objects. With each new version of the software the parametric models included will become more comprehensive and more complex. The current version of *ArchiCAD* includes a tool for the design of stairs that knows fourteen different types of stairs. This tool adds content. The *authors* of the design of the stairs are software engineers.

3.6. IKMZ Cottbus



Tool: Circle/Arc tool → PolyArc continous curve, *ArchiCAD 4.5*



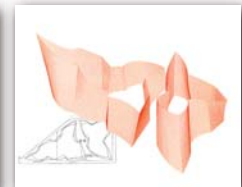
KMZ BTU-Cottbus, 6. Floor, HdM 1998

The Library building has a floor plan that is similar to an amoeba. It is the composition of a series of arcs, which seamlessly merge. It could be that the idea of geometry in this form is *derived* from the properties of the PolyArc–continuous-curve tool. For many years this was the only tool that allowed simple free curved forms in ArchiCAD. In this case the tool would have influenced the design process.

If we realize that we have an idea, we are not always able to recognize the reasons for this. How can we be sure that the ideas we develop are not *influenced* by the possibilities and limitations of the tools we work with?

3.7. Berlin Fantasy

Tool: Technical pen, *Rotring Rapidograph*



Berlin Fantasy, Philip Johnson 1993

In analogy to expressionist architecture in Germany in the twenties, in 1993 Philip Johnson designed a building for the Friedrichstraße in Berlin. Unfortunately it was not built. The walls of the outer shell of the building are assembled from a series of double-curved surfaces, which are joined with creases. If we study the published drawings, we can clearly see that large parts of them are drawn by hand with technical pens. Other parts look like a composition of printings of several screenshots. Actually, the drawings are a bricolage.

Sometimes there are *no suitable tools* capable of implementing the ideas of the design.

4. Findings from case studies

A tool may shape the formal properties of a product in a dominant way.

The choice of a tool may be part of the design process.

A tool may add content to the design. This literally extends the number of authors of the product.

A tool might be considered as the generator of an idea. This may happen intentionally or unconsciously.

There are cases, where no known tool is easily capable of implementing the ideas of the design.

5. Issues to point out

How can we prevent that the formal properties of a product are shaped by the tools more than we would like it?

How do we gain the experience to know the criteria for the choice of the proper tool?

What if we do not want to involve the work of other authors by using their tools?

How can we prevent that dealing with insufficient tools unconsciously inhibits us in the development of ideas?

What can we do if there are no suitable tools to implement the ideas of the design? What if a tool is imaginable?

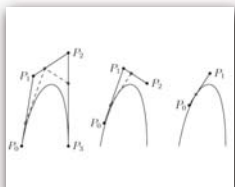
6. To design one's own tools

The artist Roman Signer produces, among other things, drawings. Instead of taking a brush or pen or chalk to use, he designed a specific tool for the task. Signer designed a remote model helicopter with a remotely triggered spray can on its bottom. This allows him to draw on oversized screens with blue color by flying the helicopter at low altitude .

Tool: Helicopter with blue spray can

Helikopter mit blauer Spraydose, Roman Signer 1997/99

Paul de Casteljau worked in the development department of Citroen. He did research on a mathematical model, which allows to accurately describe the comprehensive geometry of the bodywork of a car. In 1959 he succeeded to develop an algorithm as the foundation of his work. "De Casteljau's algorithm" generates a type of parametric curve, which is today well known as *Bézier curve*. Pierre Bézier was working for Renault, he independently invented the same curve, and published it in 1962. It was bad luck for de Casteljau that his work at Citroen, in contrary to Bézier's, had been subject to total confidentiality until 1975 [Müller, A. 1995]. In 1970, the Citroen *GS* hit the market. Its bodywork was, for the first time, completely describable with mathematics [Parizot, S. 1971]. De Casteljau reached his goal.



Tool: De Casteljau's algorithm

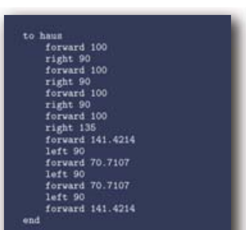
Citroen *GS,* 1970

The design of one's own task-specific design tools has itself to be considered as being part of the design process: *to design by tool design.*

7. Theses

1. To design by tool design may overcome many of the issues that occur with standard tools.
   Since one is off the beaten track. One is forced to search for design ideas in a wider field, that is to say outside the finite world of application software.
2. The development of design ideas can be enhanced by designing by tool design.
   Since it incorporates the thinking about the process of developing design ideas explicitly into the process of developing design ideas. Therefore design by tool design may introduce a meta level, a new point of view.

8. LOGO as a tool to construct tools



Logo code: haus

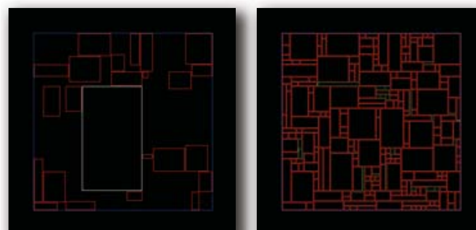
Logo grafics window

Logo is a general purpose programming language with a very simple syntax that offers the possibility of immediate graphic output and the properties of a high-level language [Harvey, B. 1997]. *Logo*, a dialect of *Lisp*, was developed in the 1960s at the Artificial Intelligence Laboratory at MIT by Seymour Papert and Wallace Feurzeig. The structural elements of *Logo* are lists of instructions that represent procedural descriptions. These elements may act as functions and commands that can be composed and nested to build new functions and commands [Downey, A. B. and Gay, G. 2003]. A function or a command can be used as a design tool. One can easily write a command to export two- and three-dimensional data as OBJ file. This file may be imported with common 3D software for further use.

9. Experiments by students

The author has been working with students of architecture, industrial design and time-based media at the University of the Arts Berlin (UdK). Typically, the students had no prior experience in the areas of scripting or programming. The seminar's goal was for students to become conceptually independent of solutions pre-made by available software; to learn to create one's own tools as a means for the development of design ideas; and to scrutinise this process as a model: may the development of design ideas be enhanced by designing the tools of design to be used?

9.1. Floor Planer



Romuald Dehio: *Floor Planer*

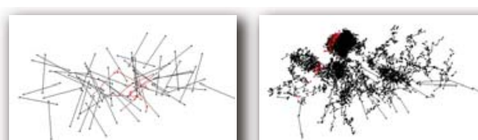
A tool that places rectangles of different size and proportion within a big rectangle without any gap. Predecessor of a tool that organizes spaces of various size in three dimensions.

9.2. Origami

Ines Bergdolt: *Origami*

A tool that folds a square sheet three times. Predecessor of a tool that can fold origami figures. The intermediate stages of the folding movement are being materialized.

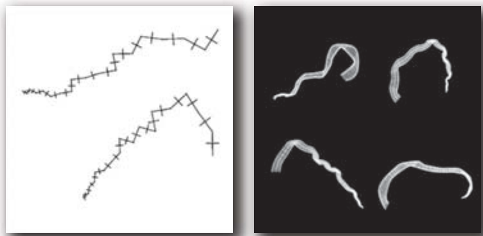
9.3. Segmentbreaker



Akitoshi Mizutani: *Segmentbreaker*

A tool to repeatedly chop a number of segments with a chopping knife, rendering nothing but powder. A tool to study mechanisms of destruction. A subsequent tool will chop three dimensional objects.

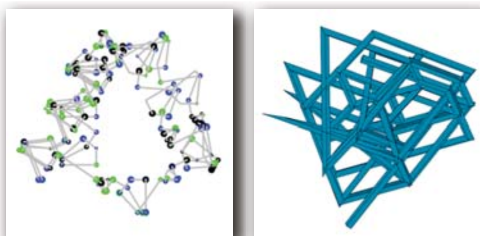
9.4. Concrete Worms



Guillaume de Morsier: *Concrete Worms*

A tool that produces the complex geometry of underground wormholes of an imaginary species of worms. Subsequent tools will be able to intervene specifically in the fabric of the city.

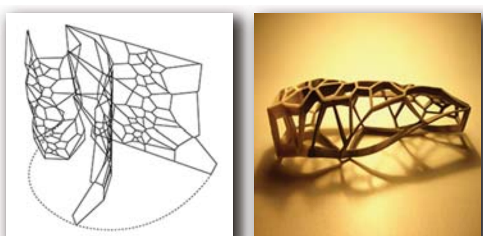
9.5. Knotted Knots



Mandy Meißner: *Knotted Knots*

A tool for reverse engineering the work of an artist. A string with the length of one kilometer is repeatedly knotted. The end product is one big knot. The tool uses a recursive process to insert knots.

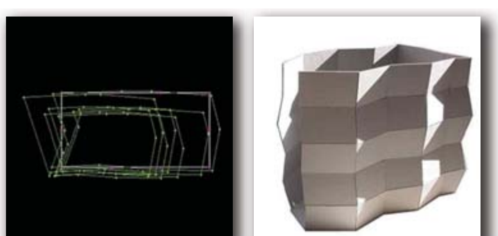
9.6. Lattice Tube



Hans-Georg Bauer: *Lattice Tube*

A tool for the production of Voronoi diagrams [de Berg, M. et al. 2000] for specific requirements. The initial data for the diagram was imported from *Rhino* to *Logo*. After the calculation the diagram was exported back to Rhino for further processing.

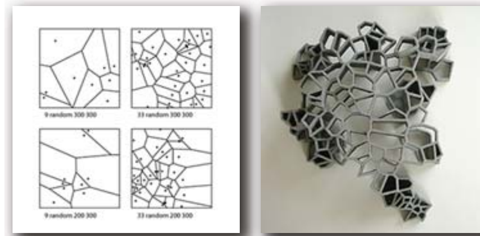
9.7. Data Mine



Andreas Garreaux: *Data Mine*

A tool for generating irregular polygonal surfaces with the main feature that all surfaces should have exactly four sides. An anti-triangulation-tool.

9.8. Pavilion



Dusanka Malicevic: *Pavilion*

A tool for the production of Voronoi diagrams for specific requirements. After its calculation the diagram was exported to *Form-Z* for further processing.

10. Findings from the experiments

The work is frequently arduous, as a small task may require a disproportionately great effort.

Designing with self-designed tools often leads to results that are clearly distinct from the majority of products designed with standard tools.

Designing with self-designed tools may be regarded as an indirect way of designing. Well-rehearsed, unquestioned ways of working are bypassed.

To discover the potential of self-designed tools has an abetting effect: to design more tools, to despise sophisticated "convenience tools", to think more in designing by tool design.

Conclusion

The development of design ideas can be enhanced by designing with self-designed tools.

A future discourse about a new aesthetic due to the rise of generative tools should not be determined by what is more spectacular or more mathematically refined. Rather, it should be about but the capacity to make use of the potential of these tools.

The questions emerging with the application of tools are so profound, that they have to be considered a substantial part of the design process. To think about and to apply design by tool design can therefore not primarily be regarded as a task for highly specialized experts. It can not be isolated and outsourced. We understand it as a genuine matter of architecture, a common good.

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Glazing Technology: the Hidden Side of Free-Form Design

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Abstract

Free-Form design very much characterises the current architectural debate. It is presently moving from complex, opaque surfaces to transparent glass skins, with the consequence that architectural forms are determined not only by the geometrical definition of the skin but also by the supporting structure, by the positioning of the glazing surface, and by the glass fixing system.
Therefore, structural issues and skin technologies are having a huge impact on the design process and must be addressed at the same time as the geometrical issues. More and more, the final result depends on technological developments.
This integration of design and technology has lead to innovative projects, such as the extension of the High Speed (TGV) Train Station in Strasbourg, where the development of the new technology of cold-bent glass allowed a new level of transparency to be reached in a double-curved envelope.
The new research on panelisation of double-curved surfaces also allows the knowledge and know-how developed for the Strasbourg train station to be applied to more articulated envelopes and free-form surfaces, thus realising new architectural forms and expression.

Keywords: Glass, Structure, Geometry, Free-form, Cold bent glass, Offset vector

1 Introduction

The interest in Free-Form is not new to architecture [8]. The Sidney Opera House and its controversial site have shown both how easy is to imagine a free and smooth shape and how difficult it is to match such a form with the structural and construction requirements.

Many years later, Renzo Piano adventured into Free-Form design with his project for the Bercy Shopping Center, probably one of the very first examples of blob architecture. In this case, he approached the problem from an architectural point of view, and he approximated the surface using families of standard flat panels overlapping each other in order to avoid the intrinsic difficulties of matching and jointing the panels.

Finally, one must mention the Guggenheim Museum in Bilbao, by Frank Gehry, where the free surfaces have been resolved using titanium sheets thin enough to adapt to the random geometry, but with the effect that the surface is not perfectly smooth. It also has a texture or a pattern as result of using smaller-sized sheet panels of titanium.

2 Transparent Free-Form

Free-Form design has the need for consistent knowledge. The creation of transparent free surfaces is even more complex, since the effect of transparency depends on what is behind the glass and therefore visible. Slenderness of structure, minimization of connections, and the appropriate resolution of glazing fixing systems have become the primary parameters governing the design process.

In the case where a surface has no more relation with translational or revolution geometry or in the case of smooth, non-facetted geometry, these parameters gain more importance. In such contexts, the design goes beyond the transformation of a geometrical form into a glass surface, to the simultaneous conception of the structure, the connections, and the skin as an integrated system where each element matches the performance of the others.

Many parameters govern Free-Form structural design, such as element standardization and the geometrical twist of structural elements which could result in misalignment at the connections. Such considerations and choices have repercussions on production techniques and on costs as well. Finally, it should not be forgotten that the structural scheme greatly affects the lightness and the pattern of the structure, and therefore, the architecture.

Moreover, glazing design is inherently rooted in the definition of the offset, the distance between the glass plane and the structural, geometrical line. For each structural geometry, several offset vectors are possible and the choice effects and controls the design of the connection. The desire to create a completely smooth surface increases the complexity of a project, compared to a facetted solution, and it also has strong repercussions on costs and feasibility. Glass sizes are also relatively limited when using single or double curvature glass.

All these considerations underlie the projects developed by RFR in the last ten years and their creative resolution at the juncture of architecture and engineering has contributed to the evolution of RFR work.

3 Standardisation

3.1. The glazed roof of the Neumunster Abbey and Jean Jaures Metro Station

Two projects, the glazed roof in the main courtyard of the Neumunster Abbey in Luxembourg [1] [2] [3] and the glazed roof of the Jean-Jaures metro station in Toulouse [2] [3] - designed in 1999 and 2001 respectively - use facetted surfaces of both quadrangular and triangular glass panels. In these two cases, the roof has not been created by assembling all different elements; rather, the structure and the glazing system are made of standardised elements.

Fig 1 – Neumunster Abbey and Jean-Jaures Metro Station

The geometry is built up using circular arches of different radii and the connections are all identical and fabricated as cast pieces. In order to deal with the variation in geometry by using only standardised elements, the orientation in space and the offset vector of each connection is always different and defined by a mathematical algorithm.The consequent digital script allowed the automatic generation of the geometry and of all the working points at a time when Catia and parametric design were not easily available in the architectural field.

3.2. The double curvature geometry of the Lentille St.Lazare

The apparently Free-Form design of the new entrance to the Gare St. Lazare Metro station in Paris [7] is generated by combining and superimposing spherical segments over a torus, which results in a bubble shape that remains a geometry of revolution. On the other hand, the orientation of the structure follows a different logic: the arcs are positioned within two sets of radial planes converging on two orthogonal lines passing from the centre of the sphere.

In order to align these two simple but different geometrical concepts, the connections were made of wax-cast pieces composed of two standard parts, assembled with different angles according to the different position. The difference in orientation between the arcs with respect to the glass surfaces was resolved by a standard detail which uses self-aligning spherical joints in order to assure the compatibility between the glass frame and the structure.

Moreover, the establishment of the arcs implies that the glass panels are all different in plan, but are derived from two double-curved shapes: the spherical and the toroidal. In this way, it was possible to minimize the number of moulds and to produce all the glass panels using only a few oversized moulds. Annealed glass, which is laminated, was used in order to assure overhead security.

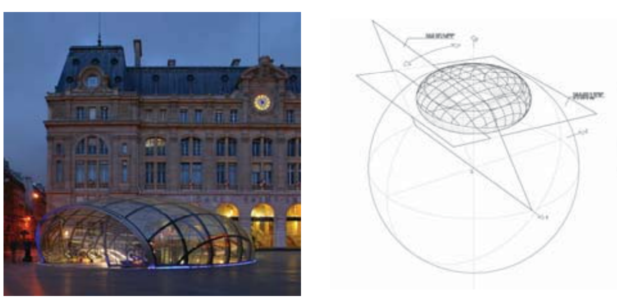

Fig 2 - Lentille St. Lazare.

4 Cold-Bent Glass

4.1. The twisted glass of the Avignon TGV station

The form of the TGV Station of Avignon [3] is the result of the intersection of two horizontal tori, which, as a geometry of revolution, allow for an easy standardisation of the structure and of the glass panels. On the other hand, the architectural decision to align the glass parallel to the building's ridge introduces a new complexity, since the glass panes cross the tori diagonally and the glass panels are not planar anymore but twisted.

Fig. 3 - Avignon High Speed Train Station

The panels are rectangular with a high aspect ratio as result of the cold-bending technique which allows the glass to form over the surface: the flat panes are elastically bent and forced onto the structure during mounting. This technique proved feasible since the stress due to twisting is negligible with respect to the stress due to the action of wind. The climate and the consequent thermal requirements demanded a double glazing, adding extra difficulties due to the sensitivity of the periphery joints to the effect of twisting. In order to contain the stresses in the sealant joints and to guarantee the long life of the glazing unit, a "pressure equalized DGU" (vitrage respirant) was developed and chosen in preference to the standard double-glazing. The sustainability of this project is based on the development of two techniques that were innovative at the time, 1997-2001: the cold-bending and the pressure equalization of the chamber of the double glazing.

Fig. 4 - Avignon High Speed Train Station

4.2. Cold-bent glass: the new challenge of the Strasbourg High Speed Train (TGV) Station

The possibilities for cold-bending glass were further developed in the extension for the High Speed (TGV) Train Station in Strasbourg [4] [5] [6] which opened in the summer of 2007.
The new roof, which covers and shelters the façade of the existing train station, consists of a toroidal, fully-glazed envelope 140 meters in length. A continuously curved surface was preferred to a facetted solution in order to emphasize the smoothness of a toroidal geometry, and, as in the case of the Avignon station, the continuity of the surface was created using only flat glass. In contrast to Avignon, the glass at Strasbourg is not twisted; rather, it was elastically bent into a cylindrical shape. According to this logic, the panels are long and narrow in order to maximize the longitudinal flexibility while still spanning transversally on a relatively short span.
The thickness of the glass comes out from the good balance between cold-bending and shell behaviour. A thin glass panel is less resistant but it has a better curvature effect, while a thick glass panel is more resistant but it works more under pure bending. At the same time, a thin glass panel is less resistant but it consumes less resistance capacity while cold-bending, whereas a thick glass panel is more resistant but its residual stress, after cold-bending, is much higher.

The cold-bending technique also depends on the nature of the support. The arcs are not circular, so that the glass panels have different radii varying from approximately 11 to 30 meters. Therefore, the cold-bending process has been optimised for the various radii, in particular the tighter ones.

Fig. 5 - Strasbourg High Speed Train Station

To directly cold-bend on site, when mounting the glass over the steel frame, was possible only for the bigger radii and not for the tighter radii where the “frozen” stress due to cold-bending would have been too high with respect to the climate stresses. In order to minimise the residual stress “frozen” in the glass, the panels are bent before, and not after, lamination. The advantage of this technique is that the panels maintain their bent shape after lamination, which simplifies the mounting process that can then be done in the usual way.
The resulting panel composition is laminated glass of two 6 mm-thick toughened panes. Due to the innovation and the large size of the skin envelope, the glazing technology and the mounting methodology were subjected to a severe testing and validation process run by the French building authorities.

Fig. 6. - Strasbourg High Speed Train Station

The Strasbourg station extension, a structure characterised by a clear hierarchy and by a pertinent technological approach, exemplifies the creation of a smooth double-curved envelope which maximizes transparency to an extent never reached before.

5 The new challenges

5.1. The Louis Vuitton Foundation in Paris

The Strasbourg Train Station extension should not to be considered as a final achievement for Free-Form design. Rather, it is one step in an on-going evolutionary process which allows the pursuit of new and even more complicated projects, such as the Louis Vuitton Foundation in Paris, designed by Frank Gehry and due to open in 2011.

The challenge in this project is to replicate the complexity of the Guggenheim Museum in Bilbao while using transparent surfaces. The geometry is developed using free-form, developable surfaces, but the degree of complexity is controlled by limiting the surface’s variations to approximations of a cylinder. The skin is created using single-curved hot-bent glass according to a limited number of families. It is cold-bent on site to adapt its curvature to the multitude of different radii required by the geometry: this two-step production technique permitted the maximum freedom of form using only a limited number of moulds.
Each glass panel spans between two curved supports that are independent from the secondary or transverse structure. This approach make the beams supporting the glass more complex , but simplify the geometry of the transverse elements, which became independent of the glass geometry.
The choice to base the design on cylindrical developable geometry displaced part of the complexity from the skin to the structure. The feasibility of this project is the result of the integration and synergy between the glazing technology and the production constraints of both the fixing elements and the bearing beams, which twist in order to follow the surface. Of course, this complexity is managed using an advanced tool like Catia that takes advantage of the parametric nature of the software. Also, Catia generated a very precise model which included all the elements of the design and gave a very good representation of what it would be in reality. Catia conferred the advantage of being able to detect and solve during the design stage all the problems that might be encountered during the construction phase.

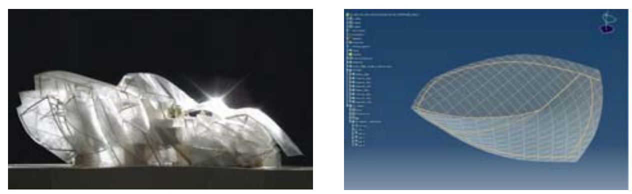

Fig. 7 – Louis Vuitton Fondation, Paris

5.2. Non-developable smooth surface

Over the years at RFR, accumulated experience has permitted an evolution and a consistent development process which is represented most strongly by the Louis Vuitton Foundation project. In parallel with this evolution, design tools have changed and passed from in-house scripts to sophisticated software such as Catia. Design options are also increased by new digitally controlled machines, which have opened new horizons in terms of productivity. These new powerful tools allow a much higher level of complexity, even though they are not a breakthrough in terms of geometrical thinking or mathematical knowledge.

In addition to the development process, a more theoretical approach can also expand geometrical knowledge and open a more radical approach to Free-Form design. Research based on the development of mathematical algorithms can lead to new technical solutions, in particular when the interest is shifted from the definition to the subdivision of the surface. Subdivision is the main point when thinking globally and trying to couple glazing patterns with structural layouts.

The current research program developed by RFR in conjunction with the Technische Universitat Wien investigates the panelisaton and subdivision of surfaces for creating non-developable Free-Form surfaces without being limited by facetted solutions, in order to realise double-curved smooth glass surfaces [9] . Appropriate subdivision of the surface can lead to optimum panelisation which can only be realised using single-curved glass. The division of the surface into discrete elements and the orientation of the panels are the key factors in guaranteeing the smoothness of the skin. These more optimal solutions can be attained thanks to newly developed algorithms and computational techniques. The uniqueness of the principle and high degree of innovation has lead to a patent on the subject.

The subdivision of surfaces and the definition of the offset vectors are therefore deeply coupled. The optimisation of the surface subdivision can lead to a simpler structure based on the reduction or the annihilation of twist at nodes, with the consequent advantage of allowing simpler details. On the other hand, new glazing technologies such as cold-bent glass are valuable for producing single-curved panels that allow the creation of smooth Free-Form design at a reasonable cost.

The first results of this research allow us to imagine new transparencies and non-conventional shapes, so that the complexities seen only in science fiction and in computer rendering are not far from being realisable, and may became a reality in the short- or medium-term.

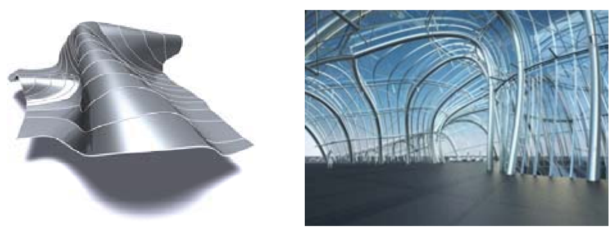

Fig 8 – Experimental geometries

6 Conclusion

Free-Form design, when dealing with transparent surfaces, is not only rooted in the geometrical definition of the surface, but depends on the correct coupling of the glazing technology with the structural constraints. These are the principle considerations for producing transparent and light skins that appear to defy the laws of statics.

In the past, in-house scripts that began by exploring simple non-uniform geometries were used to meet the challenge of building more articulated transparent surfaces. Nowadays, after having investigated script techniques, we are moving from parametric design to the creation of algorithms in order to control and manipulate the geometry. Free-Form design that is sustainable in terms of technologies, costs, and aesthetics is in the foreseeable future. Mathematics, geometry, technology and production are all converging together.

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Architectural freeform structures from single curved panels

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Abstract

The problem of covering a freeform surface by single curved panels can be treated with the concept of semi-discrete surface representations, which constitute a link between smooth and discrete surfaces. A surface composed from developable strips (called a D-strip model) is the semi-discrete equivalent of a quad mesh with planar faces, or a conjugate parametrization of a smooth surface. Using recent progress on the geometry and computation of D-strip models, we investigate their use for the segmentation into panels, for multi-layer constructions and for the supporting beam layout and manufacturing in architectural freeform structures.

Keywords: architectural geometry, discrete differential geometry, freeform surface, panelization, developable surface, developable strip model, single-curved panel, multi-layer structure, offset.

1 Introduction

Complex freeform structures are one of the most striking trends in contemporary architecture. Pioneered by F. Gehry, architects nowadays exploit digital technology originally developed for the automotive and airplane industry for tasks of architectural design and construction. This is not a simple task at all, since the architectural application differs from the original target industries in many ways, including aesthetics, statics, scale and manufacturing technologies.

Whereas metal forming can generate any reasonable shape of a car body, it is much less clear how to actually construct a complicated geometric shape in an architectural design. One has to segment the shape into simpler parts, so-called panels. Since available CAD software does not cover this topic, one may have to resort to simpler shapes, to accept higher costs or to try experimental approaches.

Very recent research shows that the use of advanced tools from mathematics and geometry processing makes a real difference in this field. An example is provided by covering freeform shapes with planar quadrilateral panels; such planar quad panels possess a number of important advantages over triangular panels: the resulting structure has a smaller number of edges, resulting in a smaller number of supporting beams following the edges, less steel and less cost; quad meshes also have a lower node complexity, which is an important advantage for manufacturing. Panelization with planar quads can be made accessible with methods from modern discrete differential geometry [Bobenko and Suris 2005; Liu et al. 2006; Pottmann et al. 2007a; Pottmann et al. 2007b].

Contemporary architecture employs different kinds of geometric primitives when segmenting a freeform shape into simpler parts for the purpose of building construction. For most of the materials used (glass panels, wooden panels, metal sheets, . . .), it is very expensive to produce general double curved panels. A popular way is to use approximation by flat panels. A third way, less expensive than the first and capable of better approximation than the second, is segmentation into *single-curved panels*. This is the topic of the present contribution, which is structured as follows: In section 2, we briefly look at available approaches and summarize some main results of our very recent research on developable strip models [Pottmann et al. 2008] and in section 3 we show a few of the many ways in which this basic theory can be applied in the actual construction of architectural freeform structures.

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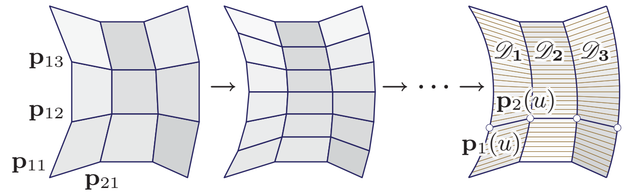

Figure 1: *Semi-discrete models as limits of discrete models. Partially subdividing quadrilateral meshes with vertices $\mathbf{p}_{i,j}$ and planar faces $\mathbf{p}_{i,j}\mathbf{p}_{i+1,j}\mathbf{p}_{i+1,j+1}\mathbf{p}_{i,j+1}$ yields, in the limit, a D-strip model consisting of developable strips $\mathscr{D}_i$. Each strip is bounded by edge curves $\mathbf{p}_i(u)$ and $\mathbf{p}_{i+1}(u)$. We call the polygon with vertices $\mathbf{p}_1(u), \mathbf{p}_2(u), \ldots$ a ruling polygon.*

2 Developable strip models

A surface which is composed of developable strips may be obtained as the limit of a quad mesh with planar faces (PQ mesh) in a refinement procedure where only the rows (or the columns) get refined; see Fig. 1. Refining a PQ mesh in both directions, one obtains a so-called conjugate curve network on a smooth surface [Liu et al. 2006]. From this perspective, surfaces composed of developable strips – called D-strip models henceforth – may be viewed as a *semi-discrete surface representation*, which constitutes a link between smooth and discrete surfaces.

There is previous work dealing with piecewise developable surfaces: Subag and Elber [2006] approximate NURBS surfaces by piecewise developables. Several algorithms have been proposed for the construction of papercraft models [Mitani and Suzuki 2004; Massarwi et al. 2007; Shatz et al. 2006]. These contributions do not aim at smoothness of boundaries and even widths of developable pieces; consequently they are not required to exploit the semi-discrete viewpoint and the relation to conjugate curve networks and PQ meshes.

We will describe here only very briefly the computation and basic geometry of D-strip models and refer to [Pottmann et al. 2008] for more details.

Parametric representation of D-strip models. A D-strip model consists of D-strips $\mathscr{D}_i$, parameterized by $\mathbf{x}_i(u, v)$, and joined together along edge curves $\mathbf{p}_i(u)$ as shown by Fig. 1. We describe the edge curves as B-spline curves and thus the D-strips as ruled B-spline surfaces,

$$\mathbf{p}_i(u) := \sum\nolimits_j B^3(u-j)\,\mathbf{b}_{i,j}, \qquad (1)$$
$$\mathbf{x}_i(u,v) := (1-v)\mathbf{p}_i(u) + v\mathbf{p}_{i+1}(u).$$

Here B^3 is the cubic B-spline basis function for integer knots.

In order to approximate a given surface Φ by a D-strip model, we compute the control points $\mathbf{b}_{i,j}$ in an optimization algorithm by minimizing the target functional

$$\lambda_1 f_{\text{dev}} + \lambda_2 f_{\text{prox}} + \lambda_3 f^{\partial}_{\text{prox}} + \lambda_4 f_{\text{fair/edge}} + \lambda_5 f_{\text{fair/ruling}}. \quad (2)$$

Its individual terms measure developability of the strips, closeness to Φ, closeness to the boundary curve $\partial\Phi$ if necessary, and fairness. Developability of the final surface has the nature of a constraint, which is achieved by letting λ_1 grow during iterative optimization.

The individual terms are defined as follows. *Developability* of the surface is expressed by a small value of

$$f_{\text{dev}} = \sum\nolimits_i \int \delta_{\mathbf{p}_i,\mathbf{p}_{i+1}}(u)^2 du.$$

Here, the integrand denotes the squared distance of diagonals in the quad $(\mathbf{p}_i, \mathbf{p}_i + \lambda_i \dot{\mathbf{p}}_i, \mathbf{p}_{i+1} + \mu_i \dot{\mathbf{p}}_{i+1}, \mathbf{p}_{i+1})$, where dots indicate differentiation with respect to u. Those quads have to be planar for a developable surface. To give the distance a useful meaning, we choose $\lambda_i = \|\mathbf{p}_{i+1} - \mathbf{p}_i\| / \|\dot{\mathbf{p}}_i\|$ and $\mu_i = \|\mathbf{p}_{i+1} - \mathbf{p}_i\| / \|\dot{\mathbf{p}}_{i+1}\|$.

Proximity to a reference surface Φ is guided by

$$f_{\text{prox}} = \sum\nolimits_k \text{dist}(\mathbf{x}_k, T_k)^2.$$

Here, $\mathbf{x}_k$ are sufficiently dense sample points on the strip model and T_k are the tangent planes of the reference surface Φ at the points $\mathbf{y}_k \in \Phi$ which are closest to $\mathbf{x}_k$. Hence, we minimize squared tangent plane distances, which is known to yield better convergence than employing squared distances $\|\mathbf{x}_k - \mathbf{y}_k\|^2$ to closest points. For measuring distance to the *boundaries* of Φ, we use tangents t_k at boundary curves instead of tangent planes,

$$f^{\partial}_{\text{prox}} = \sum\nolimits_k \text{dist}(\mathbf{x}_k, t_k)^2.$$

For certain applications it is reasonable to approximate discrete reference points $\mathbf{y}_j$ by the edge curves $\mathbf{p}_i$ instead of a smooth surface Φ, e.g. if one has laid out a supporting structure with fixed mounting points beforehand. In this case we employ the target functional

$$f_{\text{prox,discrete}} = \sum\nolimits_j \text{dist}(\mathbf{y}_j, t_j)^2,$$

where t_j denotes tangents at points $\mathbf{p}_i(u_j)$ which are closest to $\mathbf{y}_j$. *Fairness* is measured with linearized bending energies of edge curves and ruling polygons:

$$f_{\text{fair/edge}} = \sum\nolimits_i \int \|\ddot{\mathbf{p}}_i(u)\|^2 \, du,$$
$$f_{\text{fair/ruling}} = \int \Big(\sum\nolimits_i \|\mathbf{p}_{i+1} - 2\mathbf{p}_i + \mathbf{p}_{i-1}\|^2 \Big) \, du.$$

The iterative optimization algorithm is based on a Gauss-Newton method with Levenberg-Marquardt regularization.

Initializing optimization. There is a close relation between PQ meshes, D-strip models and conjugate curve networks. Therefore it is feasible to initialize the control point mesh either with a PQ mesh approximating Φ or a conjugate curve network of Φ. As an example for the second possibility we consider the following common architectural problem:

Given is a family of planar and parallel sections $\mathbf{c}_i$ of Φ, which should be approximated by the edge curves $\mathbf{p}_i$ of the D-strip model. This amounts to prescribing one family of curves of a conjugate curve network. Developability of a resulting D-strip is characterized by constant tangent planes along rulings. Thus it is reasonable to initialize the control point mesh by points on $\mathbf{c}_i$ corresponding by parallel curve tangents. Figure 2 shows a real example utilizing floor slabs as sections.

Principal strip models. When approximating a surface by a D-strip model, it is natural to let edge curves follow the principal curvature lines of maximal curvature and to place rulings along the directions of the smaller principal curvature. Rather than first computing principal curvature lines and then deriving a D-strip model, we can work within the semi-discrete setting and define *principal* strip models (circular and conical models) which may be seen as limits of circular and conical meshes. These models possess remarkable geometric properties which are important for the actual architectural application (see section 3).

For brevity, we confine here to conical models. Recall that a PQ mesh is *conical* if all vertices have an associated right circular cone which is tangent to the faces adjacent to that vertex. By refinement in one direction, we get the semi-discrete version:

Conical strip models (Fig. 2): Each point $\mathbf{p}_i(u)$ of an edge curve is the vertex of a rotational cone which is tangent to the two adjacent D-strips along their rulings. Hence, the tangent forms the

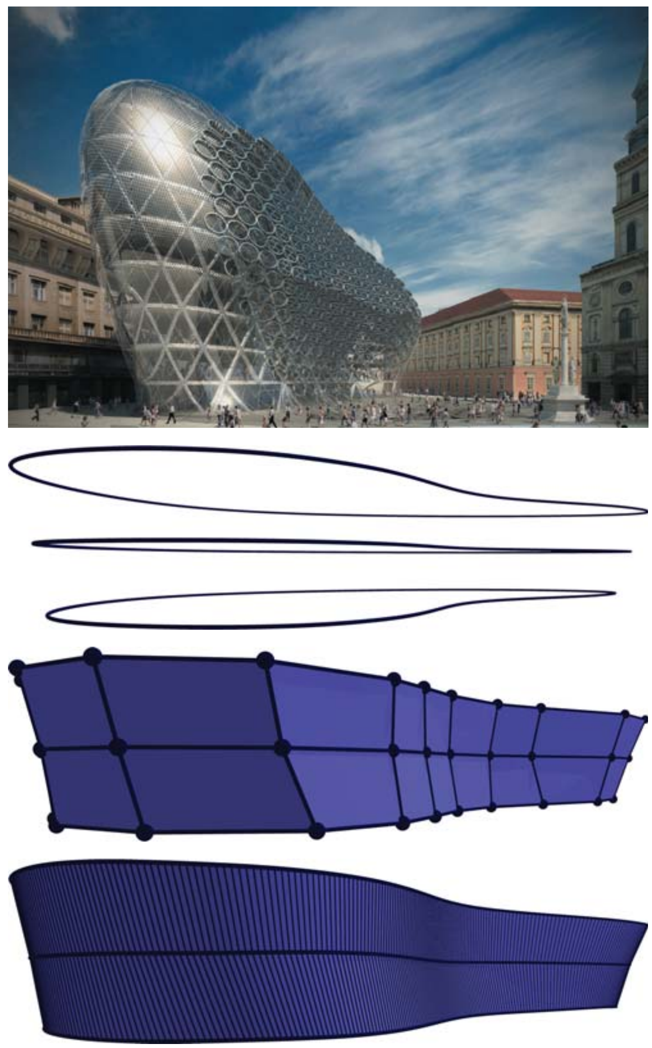

Figure 2: *Szervita Square, Budapest. A project designed by Zaha Hadid Architects. Example of approximating the outer shell by a D-strip model aligned with planar, parallel sections given by the three lowermost floor slabs. Sections, corresponding points used for initialization and the resulting D-strip model are shown from top to bottom. The D-strip models may be used for a further approximation using flat panels and cylinders.*

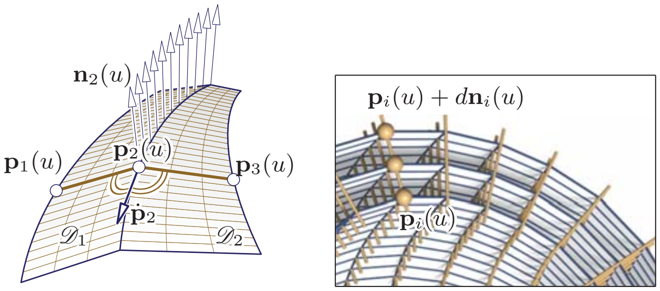

Figure 3: *Left: A conical D-strip model is characterized by a simple angle equality between the edge curve tangent and the rulings meeting there. Right: Conical models possess conical offset models at constant distance d which appears between corresponding rulings and tangent planes.*

same angle with these two rulings. Optimization towards conical strip models makes use of a geometry functional which penalizes deviation from this angle equality.

The axis (properly normalized direction vector $\mathbf{n}_i(u)$, see [Pottmann et al. 2008] for details) of the cone with vertex $\mathbf{p}_i(u)$ plays the role of a surface normal. A conical model M possesses offsets M^d with edge curves $\mathbf{p}_i(u) + d\mathbf{n}_i(u)$; rulings and tangent planes of M^d lie at constant distance d from the rulings / tangent planes of M. The ruled surfaces (sets of cone axes) which connect corresponding edge curves of M and M^d are developable (Fig. 2, right).

It is shown in [Pottmann et al. 2008] that analogous properties hold for circular strip models. Moreover, conical and circular models are closely related and can be converted into each other by simple constructions.

Geodesic strip models. A geodesic curve c on a surface Φ is a (locally) shortest path on Φ and therefore it is also a geodesic on the developable surface D tangent to Φ along c. The geodesic curve c is mapped to a straight line in the planar unfolding of D. If we glue a straight paper strip onto a physical surface model it follows along a geodesic and therefore geodesics may guide the alignment of wooden panels (Fig. 4, left) or other panels with a nearly straight development.

A geodesic curve on a smooth surface Φ has osculating planes orthogonal to Φ. In the semi-discrete case, we therefore define that a D-strip model is a *geodesic model*, if the osculating planes of edge curves bisect adjacent strips. Note that such bisector planes are reasonable planes "orthogonal" to the strip model (which is itself not smooth); if the strip model converges to a smooth surface, those planes converge to exactly orthogonal planes. Each edge curve of

Figure 4: *Left: Assembly of wooden strips onto the framing for the interior of the Disney Concert Hall (courtesy Gehry Technologies). Center and Right: Example of a simple geodesic strip model and its development. An edge curve of the geodesic model leads to oppositely congruent curves in the development (blue curve pair).*

Figure 5: *Geodesic D-strip models (in total five) which cover the interior of a freeform surface.*

a geodesic model has *oppositely equal* geodesic curvatures with respect to adjacent strips. Consequently, developing these strips yields *oppositely congruent boundaries* (see Fig. 4). The properties of strips imply that the development of the single strips is approximately straight. It seems feasible to cut them out of long rectangular panels. Typically a freeform surface is covered not by one, but by several geodesic D-strip models (see Fig. 5).

For Fig. 5, optimization was initialized by conjugate curve networks, where one curve family consists of geodesics. Optimization employed a term for well distributed strip widths. For the geodesic property, we used a functional which penalizes deviation of the edge curves' osculating planes from the bisector planes of adjacent strips.

3 Architectural structures with skins from single curved panels

The geometric properties of D-strip models, in particular principal models, give rise to a variety of possibilities for the realization of architectural freeform structures with single curved panels. We focus here on two topics only: (i) *multi-layer constructions* and (ii) *supporting beam layout*.

Given a conical model M, we may segment it into single curved patches via edge curves and selected ruling polygons. Connecting these patch boundaries with the corresponding ones on an offset model M^d, we obtain a "box shell structure" composed of curved boxes each of which is bounded by two planar faces and four developable patches (see Fig. 6). The faces which connect M and M^d are suitable for the layout of supporting beams. The strips on M (and maybe also M^d) may be covered by actual panels. Exploiting manufacturing tolerances, one can try to approximate the individual developable patches by simpler ones, namely cylinders or cones.

The close relation between PQ meshes and D-strip models can be exploited to compute multi-layer structures which exhibit both types, e.g. a PQ mesh for the beam layout and a D-strip model attached to it for the actual panels. Especially if the two principal curvatures of the design surface are not too different, one may consider a structure composed of two D-strip models where the discrete direction of one strip model is aligned with the smooth direction of the other model and vice versa (Fig. 7).

Offsets also simplify the beam layout and manufacturing (Fig. 8): For any conical model $M = \{\mathbf{p}_i\}$ with strips $\mathscr{D}_i$, there are developable strips $\mathscr{N}_i$ which connect corresponding edge curves $\mathbf{p}_i$ and $\mathbf{p}_i^d$ of M and an offset model M^d. We let the stem of a curved I-beam follow $\mathscr{N}_i$, while its horizontal bars follow D-strips orthogonal to $\mathscr{N}_i$ (as shown in [Pottmann et al. 2008] these D-strips may

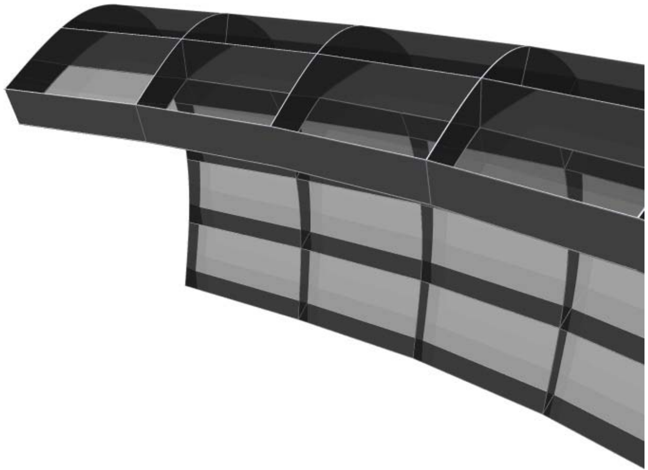

Figure 6: *Box shell structure derived from an offset pair of conical strip models.*

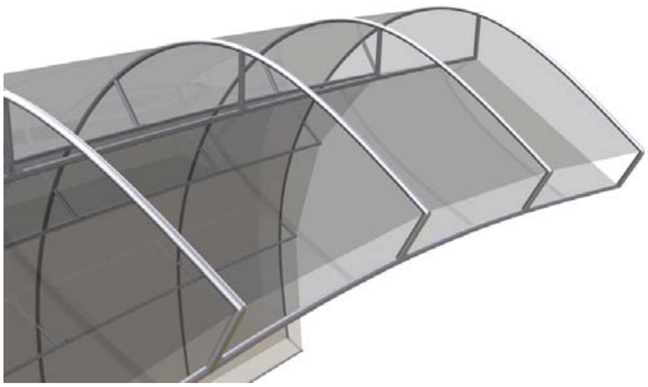

Figure 7: *Multi-layer structure formed by two D-strip models interpolating parallel PQ meshes.*

be obtained via conversion to a circular model). Glass panels are aligned with further offset models. A technique for mounting the panels is sketched in Fig. 9.

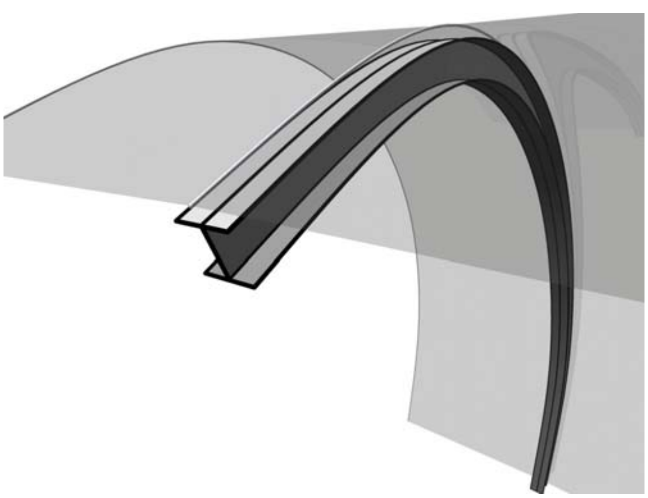

Figure 8: *Positioning a curved I-beam with developable stem and developable horizontal bars along the edge curve of a conical model.*

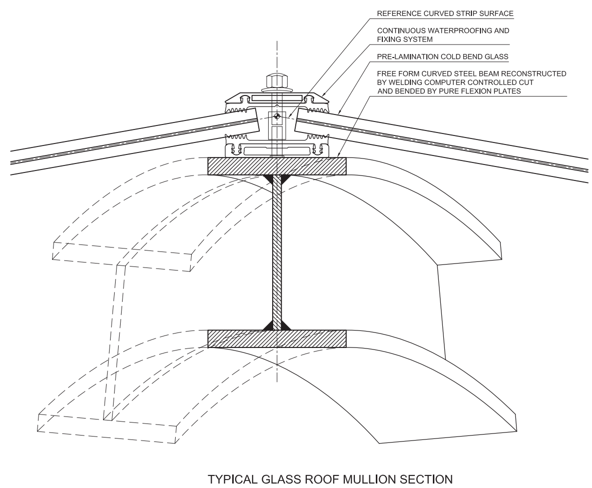

Figure 9: *Connecting the panels to the supporting beam.*

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We are grateful to Heinz Schmiedhofer, Johannes Wallner and Wenping Wang for their contributions to the research published in [Pottmann et al. 2008] which forms the basis for our ongoing work on architectural structures from single-curved panels. Furthermore we thank Zaha Hadid Architects for kindly permitting us to reference the Szervita Square project.

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Generative surface smoothing and automated analysis model processing

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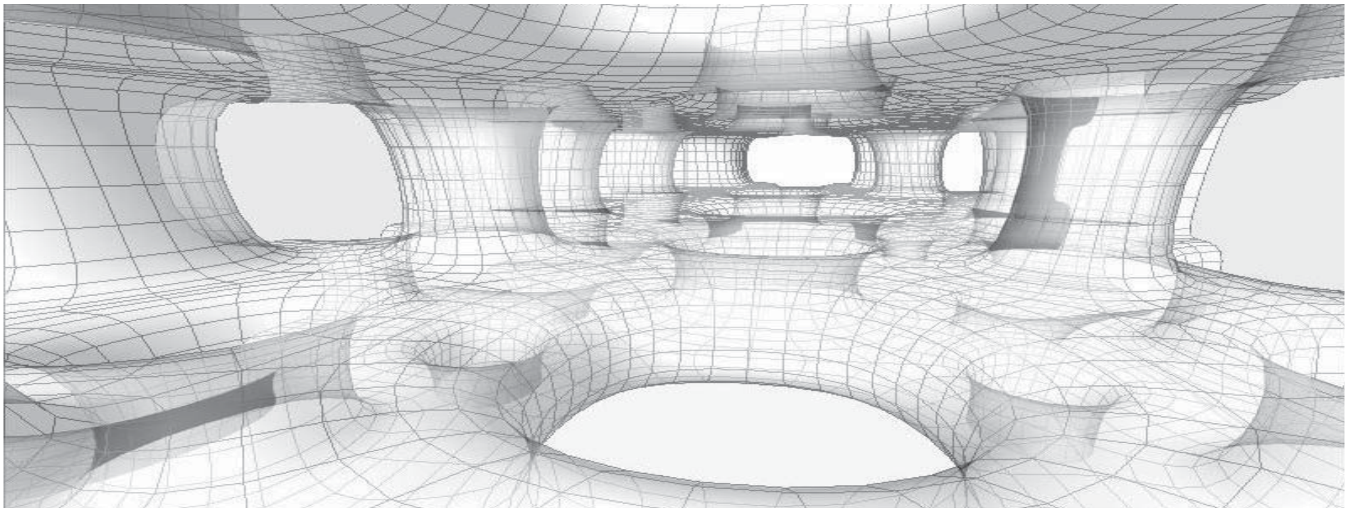


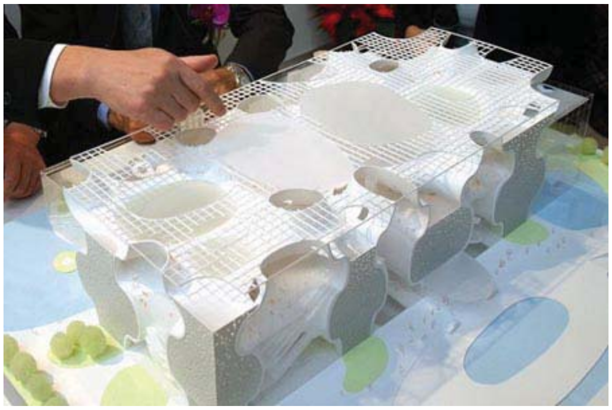
Keywords: Smoothing algorithms, Analysis automation

1 Introduction

Toyo Ito's winning competition proposal for the Taichung Metropolitan Opera House comprises exciting challenges regarding complexity of the geometry and its structural analysis. To realize the ambitious design Arup's Advanced Geometry Unit developed a series of specific geometry and structural model generating tools.

2 The Emerging Grid

The intention was to create a space without orientation. A perimeter boarder is given by a rectangular box in which continuous surface is placed. This surface divides the space into cavities which could be either an exterior or interior part of the building.

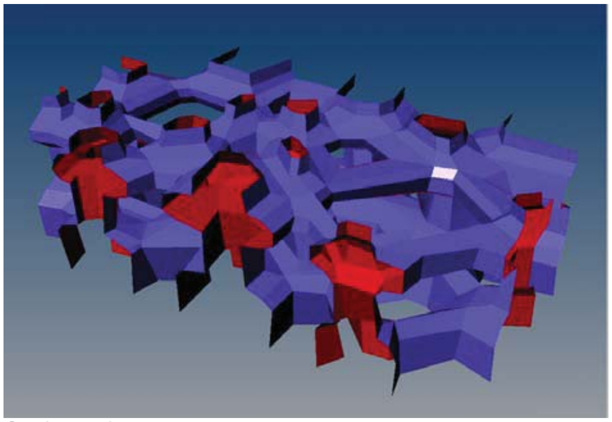


Competition Model

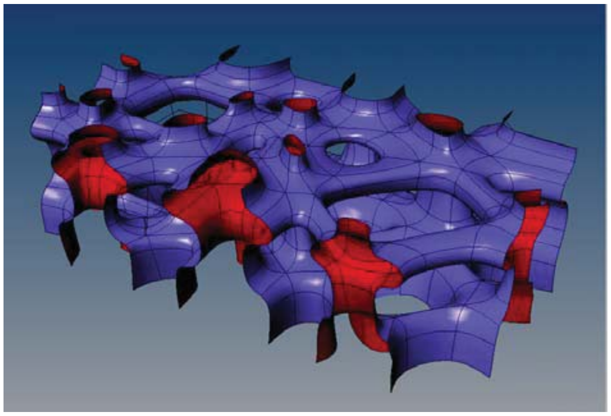
The smoothness of the surface is not only favoured for aesthetic reasons but is essential to obtain an efficient structural system. The shell type structure doesn't distinguish between wall and slab as their transitions are accruing continuously.
By using a smoothing subdivision algorithm like Catmull Clark the surface is controlled by an array of polygonal quad facets which are providing the starting geometry for the process. Each facet is subdivided into a new set of vertices and then averaged between their adjacent neighbours. The crude starting grid densify and transforms – it is emerging.

3 Geometry Smoothing Process

The prototype of the algorithm was initially developed for the concrete shell roof of the Arnheim Central Station. Composing a complex surface from multiple single NURBS patches and also preserving a smooth transition of curvature along the seams is still a challenge for current CAD software.
The adopted smoothing algorithm is able to describe an infinite surface as a single object. Smooth transitions are ensured by the process and generated by the interpolation of the neighbouring vertices.

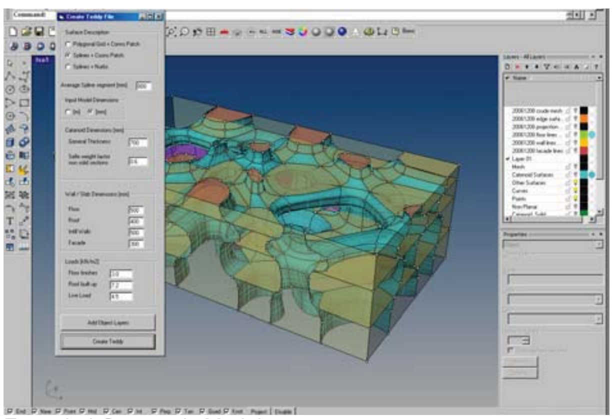


Crude mesh geometry



Smooth mesh geometry

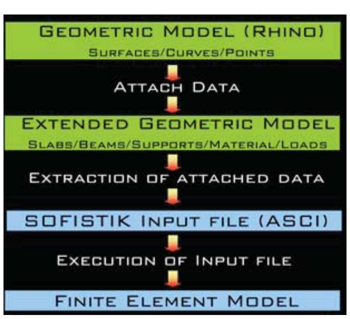
To gain full control over the process and the ability to extract specific data during the execution the algorithm was programmed from scratch by using Rhinoceros as visualisation engine. Specific requirements which were requested by the project's geometry are added to the process. All vertices which are coinciding with the subscribing box are constrained on this perimeter and are only allowed to perform a 2D smoothing.
After the smoothing is performed and a new set of geometry objects is created wherein topology and connectivity of the elements are detected and as user data attached to the drawing objects to create an extended geometric model.



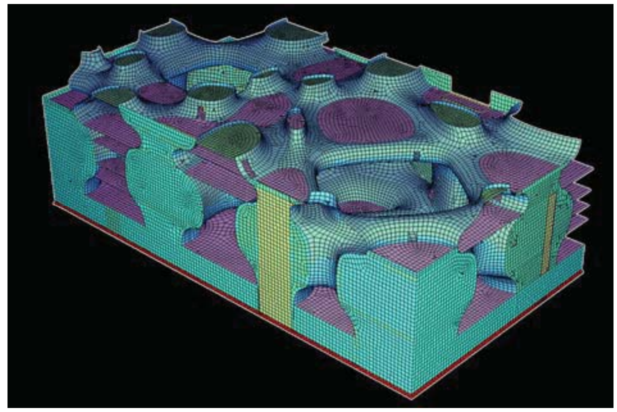
Extended Geometric Model

4 Structural Model Generation

The software which is used to analyze the structure requires only the edge curves of a doubly curved surface to execute an inbuilt meshing algorithm which approximates the area with a so called coons patch. A wire frame of edge curves and their corner points is sufficient to describe the whole structure.

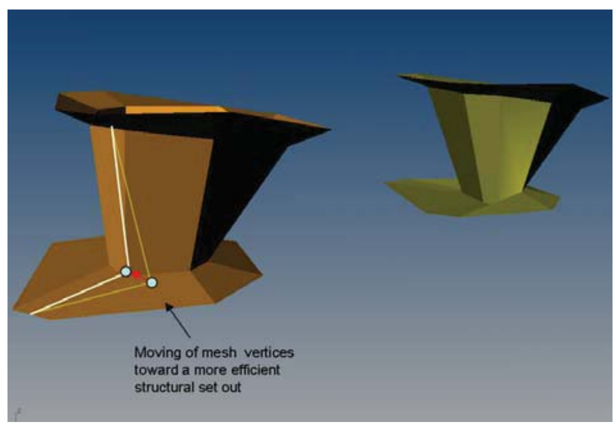


The algorithm browses through all geometry elements of the extended geometric model extracting their attached topology and connectivity data and writes a simple ASCI input file which can be executed instantly in the FE package. Also loading patterns, support conditions and material data is already included in the processed model.

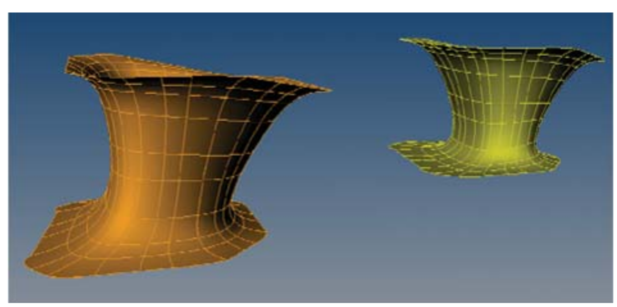


FE mesh from executed Input file

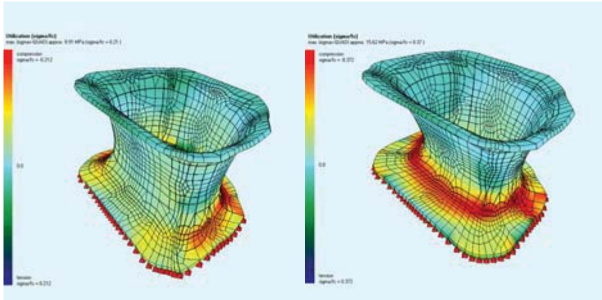
The minimum data set which needs to be communicated with the architect is reduced to the crude mesh information. The developed tools enable to create the structural model in and optimized process and to gain almost an instant response to architectural design changes. In reverse structural optimized versions of the mesh geometry can be proposed and communicated back in the same way.



Manipulation of the vertices



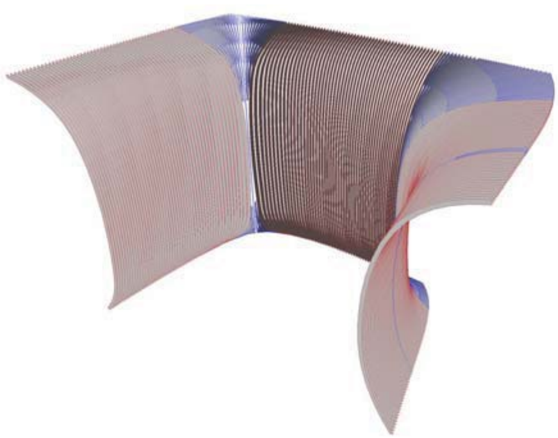
Performed Smoothing



FE-Analysis showing increased structural performance

5 3D Surface Construction Method

To develop a construction method to realize the free form geometry has been an equally challenging task for the design and engineering team.
After a series of comparative studies, the team concluded that the Truss Wall System (TWS) developed by Asahi Glass Build-wall (AGB) is best suited for the project.
TWS creates 3D surfaces from series of parallel 2D form defining non structural reinforcement trusses. Continuous 3D surface is divided in to parallel and radial zones based on the pre-smoothed crude mesh geometry.



Digital Truss wall stet out

Structural reinforcement is placed over the geometry defining truss cage to facilitate off site fabrication as much as possible. Over the structural reinforcement, 3 layers of steel wire mesh are attached with appropriate cover distance to form the doubly curved formwork.
Wire mesh is attached to the cage at 200mm pitch to control the geometry and to avoid the excessive deformation during concrete casting. This enables the 3D form to be approximated without expensive 3D tooling such as CNC milled Styrofoam.

Welding of reinforcement truss

Pre assembled Truss wall

Concrete is cast in situ and rendered manually after the structure is cured to the required strength. Rendering thickness of 25mm absorbs the construction tolerance and the out of plane deformation of wire mesh due to the hydro static pressure of concrete prior to curing.

Full scale Mock up after pouring

Acknowledgements

Construction photos are from the full scale mock-up study of the construction method commissioned by Toyo Ito & Associates, Architects, constructed by Takenaka Corp, and AGB with construction advisory team from the engineering division of the two companies.

Construction and physical competition model photos courtesy of Toyo Ito & Associates, Architects, Takenaka Corp, and AGB.

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mem[e]brane development as a case study for approaching architecture as a complex network of interactive spatial components

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Abstract

Treating architectural systems as networks of interconnected, material and immaterial, autonomous objects is an approach that may deliver appropriate foundation to creation of interactive architecture. This approach is based on the idea of considering architectural constructs as dynamic networks. Nodes of these networks may be building components, human users or other relevant entities, which dynamically and continuously interact with each other. What results from this approach, are intrinsically open and extensible, dynamic and pro-active architectural creations.

The mem[e]brane initiative presented in this paper is a collection of ongoing prototypical experiments aiming at materializing this vision. Despite differences in scale and building techniques, all mem[e]brane designs function as interactive surfaces, dynamically affecting the amount and degrees of connections between distinct spaces.

Keywords: interactive architecture, complex spatial networks, decentralized systems, dynamic geometries

1 Hyperbody vision: the next generation of architecture

Contemporarily, the development of radically new architectural qualities has become a necessity. Changes in lifestyles and cultural shifts are faster, more radical and, like never before, highly unforeseeable. On the other hand, the global society of today calls for architectural solutions that are capable of sustaining themselves in such, like never before dynamic, environments.

Saying that architecture has to be sustainable means that buildings have to be able to sustain themselves, instead of being sustained by others. However, environments in which architecture normally performs consist of many layers; the natural, the social, the cultural and many more. All of them involve local and global ecologies of numerous possible kinds. If demands towards a building, coming from any factor of such an intricate environment, suddenly change, that building, in order to sustain itself, would have to adapt its spaces to accommodate all those new demands. Otherwise, it would have to somehow encourage its users, or any other elements of its environment, to alter their original spatial needs. In any case, serious consideration of these logical ideas implies that architecture has to develop some kind of ability to instantly react to unpredictable and rapid changes in its surroundings.

While doing this, architecture also has to stay efficient. It has to actively perform at top level. It has to provide just spaces that are in various ways required from it. Buildings should also efficiently deal with energy use, potentially even providing energy rather than consuming it. However, what's most important is that architecture has to maintain its reliability and firmness. Or, to put it all in other words; architecture has to satisfy diverse demands of its users and of its environment, while also having to communicate and deal with its own limits. This means that buildings and their spaces cannot just be our blind savants. Instead, they have to become partners in a dialogue, not only responding to our actions and demands, but pro-actively shaping our lifestyles and activities. To put it all in a one-liner: architecture has to become interactive.

Interactive buildings will be more than simple customizable spaces. They will posses all features of traditional architecture, but in addition to that, they will also have a subtle will of their own. They will serve people by creatively coming up with features that, depending on their constantly improving knowledge, will holistically benefit their users and environment. Self validation of their actions, based on constant flow of responses coming from people and the environment will lead to constant development of their behaviour. Interactive architecture will also provide unprecedented experiences and aesthetics; ones, which are not just singular outcomes of a static design vision, but which will be continuously evolving processes, never repeating same behavioural patterns. In this way, architecture will soon become a new kind of an active, multidimensional medium, mediating not only between individuals, but between entire social groups.

2 State of the art in interactive architecture

In its essence, interactive architecture is not a new idea. On one hand, any architecture capable of accommodating change and in this way maintaining an ongoing dialogue with its users can be considered as interactive. Structures found in nomadic settlements or simple favela houses can be easily reconfigured whenever there is need for their spaces to be adjusted. In this way it may be stated that simple architecture like that responds to user demands by generating new spatial conditions. Informed in this way, users may trigger new reconfigurations, depending on their satisfaction with the space. This "dialogue" may theoretically last forever. However, ironically, the more technologically advanced it gets, the more likely it is for architecture to loose its interactive features, for which the indeterminacy of building setups is a prerequisite.

Advanced technologies are used in building automation systems to control HVAC installations, lighting and other commonly dynamic building features. However, the ways in which building automation systems normally operate is not interactive, but pre-programmed and reactive.

Fig. 1 ADA and Media House

There have been various experimental projects trying to introduce interactivity to high-tech architecture. Among the most renowned we can find the Media House project and ADA – the intelligent room project. The Media House is a reconfigurable space containing processing, sensing and actuating within its modular components. Ada is a room in which floor tiles individually gather input from their environment and act accordingly, developing playful interactions with users of the space.

3 Hyperbody research: theory by practice

Hyperbody has developed a unique approach towards investigating solutions for the development of interactive architecture. Our extensive theoretical research has always been instantly accompanied by creation of working prototypes that validate and illustrate in a tangible way investigated technologies and possibilities. Since the year 2003, conceptual working models of architectural objects have been built to exemplify in a playful way new possibilities of dynamic architectural creation.

Fig. 2 Samples of past works of Hyperbody

After a series of successful experimental developments, Hyperbody has reached the point from which more structured further steps need to be taken along the path towards the full featured development of the next generation of architecture. Our research has built up a substantial knowledge base allowing us to address more practical problems and to create more advanced, reliable and professional products. Hyperbody has formulated the project agenda for the coming years, which consists of several long term projects, each of which ultimately leads to creation of a large scale built structure. The projects include a multifunctional building, an adaptive environment on urban scale, building interior and a pro-active spatial surface - mem[e]brane. On the way to reach the realization of these long term goals, shorter sub-projects will be conducted in order to validate chosen approaches and methods, and to promote longer term research in progress, while potentially serving other practical purposes.

4 Mem[e]brane concept

The Spatial Membrane idea is based on a generic concept of an active surface inserted between two distinct spaces. Such surface can behave as an active membrane. This means that depending on many factors, it can stimulate emergence of either a connection or a boundary between the two separated spaces. Furthermore, it can actively generate and modify various spatial conditions on its two sides.

Fig. 3 Mem[e]brane concept render

A mem[e]brane can include many functional features. If applied on small scale, apart from its primary role as a space organizing object, it can provide many more practical qualities to the affected spaces. If applied on a larger scale, the range of possible functional implementations becomes even greater, giving mem[e]brane potentially a role of a communication medium not only between individuals, but between entire social groups. What's most important, however, is that all these features are to be provided in a dynamic manner, as an intelligent derivative from information gathered by mem[e]brane from its surroundings. The process governing the behaviour of mem[e]brane will constantly improve its logic, given the ability to learn from different precedent situations and their effects on the environment and people.

5 Explorations

Applications of the mem[e]brane idea can vary in scale and technique. For this, Hyeprbody experiments with various material techniques that may be potentially used for creation of interactive structures. Presented explorations are either autonomous assignments or were parts of broader projects. In all cases they were prototyped and operating on a basic level, but require more work to deliver fully operational final products. All physical prototypes have been destroyed in the devastating fire of the faculty of Architecture at TU Delft. Nevertheless, saved documentation allows for reconstruction of all lost material.

5.1. Cushion system

An inflatable cushion with embedded fluidic muscles and a microcontroller can become an interactive pneumatic "brick" of a dynamic membrane. Capable of two-axial bending and extendable with a variety of sensors, connected in this way to its environment and to other elements, each brick can develop a wide variety of primitive behaviours. As a result, the whole structure consisting of a higher number of such elements can produce very intricate effects and reactions.

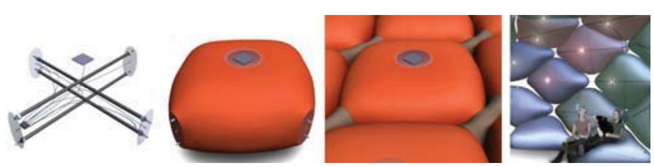

Fig. 4 Cushion system rendered details

5.2. Flex system

Another possible solution to achieve an active bendable surface involves a flexible fibreglass skeleton, filled by inflatable panels embodying a fluidic muscle component. In this case, the surface deforming forces would be internally produced within the triangulated surface structure, consisting of tensile forces of fluidic muscle and bending fibreglass counter reactions.

Fig. 5 Flex system rendered concept and prototype

5.3. Flap system

Fig. 6 Flap system, rendered concept

The next system has been designed using electric linear actuators and stiff, lightweight surface elements connected with hinges and ball-joints. In this setup diverse assemblies are possible. Not only kinetic but also visual and sonar actuation is embedded in this project, paired with rich sensing and information collecting capabilities, synchronized by learning and data processing algorithms

5.4. Dynamic openings – skin portal

Hyperbody includes the design and making of interactive installations in its education programme, where students on bachelor and master levels build interactive installations in close cooperation with Hyperbody researchers. This year the theme of those installations has been "interactive portals", a dynamic, real-time data exchanging network of installations that in the applied manner explore the possibilities of creating spatial forms that connect distinct spaces. This project hasd been a collaboration with the faculty of industrial design at TU Delft and its outcomes are to be exhibited both in Delft and at the international architectural expo in Seville, starting in September 2008.

Fig. 7 Skin portal prototype

One of the installations in this series, the skin portal, investigated dynamic possibilities of creating openings in surfaces, by applying axial forces to flexible, linear elements constituting the building skin. In this way openings could be created rapidly, in any part of the spatial division.

5.5. Distributed approach – leaf portal

The other installation of the interactive portals series has been designed and prototyped as constituting of completely autonomous surfaces, capable of curling up from a flat to a fully folded state and dynamically changing their orientation. In this way spaces were formed spontaneously and could entirely disappear.

Fig. 8 Leaf portal prototype

6 Projects

Next to ongoing explorations in design of interactive building components, Hyperbody has also formulated a number of projects aimed on testing developed concepts in real-life situations. This should ultimately provide knowledge to implement the mem[e]brane commercially and to solve a wide variety of complex spatial problems. At the time of writing this article, projects presented further were in the early design phase.

6.1. Exhibition pavilion

On the path of its commercial development, the mem[e]brane concept can be quicker and more feasibly developed and validated on the partly limited experimental scale. For this, Hyperbody initiates a project which can lead to a prototype development with the function of a dynamic exhibition space. The project can result in a tangible outcome of an elaborate exhibition stand installation, planned to be finished in the beginning of 2009.

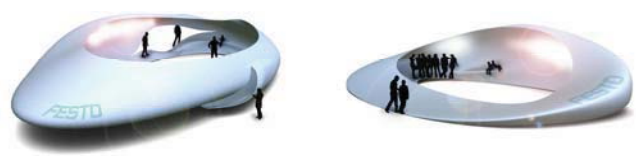

Fig. 9 Exhibition pavilion rendered concept

The project consists of a looped intelligent membrane, functioning as the main spatial component of an indoor exhibition installation. This system would provide dynamic emergence of spaces varying from a half open-space, through a semi-enclosed space to a fully separated one. A membrane can consist of a number of connected autonomous segments which can serve as spatial divisions, but also seating places, display stands or sound and light sources. Acting as a whole, the entire installation would exhibit properties of an ambient living organism. In this way it could provide adaptive spatial conditions by learning how to respond to variable information, coming directly and indirectly from exhibition visitors and organizers. At the same time a top-down override mode could directly force certain behaviour of the entire setup in order to bring it to one of preset configurations when necessary.

A number of technical solutions need to be tested in order to select building techniques which will provide best balance between the range of movement, structural stiffness, stability, strength, slimness, possibility of dynamic openings in the surface, aesthetic qualities and cost. Several options have already been investigated within educational context of the Hyperbody, although limited resources and lack of open access to preferred technologies still hinders the development of many potentially applicable solutions.

6.2. A2 mem[e]brane – long term vision

Fig. 10 A2 mem[e]brane vision

On the large scale agenda of the mem[e]brane development, Hyperbody, together with architectural design office ONL [Oosterhuis_Lénárd], has initiated the project combining the cutting-edge research of Hyperbody with efficient project design and execution capabilities of the ONL office. Collaboratively designed A2 mem[e]brane is to become an unprecedented kind of object. Stretching along the edges of the A2 highway it will combine features of a sound barrier and a landscape body, while fulfilling many functional tasks such as sound protection, fine dust collection, visual separation, lighting and traffic control. However, in addition to it, the A2 membrane will also become an element which connects the social ecologies of areas surrounding the highway with the ecology of the highway itself. It will appear dynamically only if needed, as a consequence of the mediation between the swarm of cars passing through the highway and people inhabiting and using the surrounding spaces. In some aspects it will develop a barrier, in other it will become a connection. In all cases the A2 membrane will constantly, intelligently adapt to varying conditions of its environment and will dynamically interact with it, becoming a new kind of spatial inter-medium.

Fig. 11 A2 mem[e]brane operation dynamics – rendered concept

The A2 mem[e]brane is planned to be the first of the series of the full-scale, commercially applied interactive projects of the Hyperbody-ONL collaboration.

7 Acknowledgements

To co-involved Hyperbody staff and students and to Professor Kas Oosterhuis for supervising and directing the presented projects and research

Figure 1.1 source: http://www.omnispace.org

Figure 1.2 source: http://www.media.mit.edu/physics/publications/papers/04.10.sciam/

Figure 2-11 source: Hyperbody, TU Delft, the Netherlands

Planar Hexagonal Meshes by Tangent Plane Intersection

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Abstract

The panelisation of freeform surface is still a challenging task for architectural designs. While the realization of double curved surfaces is possible with the use of advanced CNC production techniques, the technical and financial efforts for this are still extraordinary. Rationalized solutions involve the panels cut from prefab plane materials like float glass or sheet metal, however planarity for such panels cannot be reached easily. Standard triangulated solutions pose an unpleasing option Many natural phenomena show a typical hexagonal pattern. This paper is treating methods to generate planar hexagonal meshes for virtually any freeform surfaces by the intersecting of tangent planes distributed over the surface - this method will be furthermore referred to as Tangent Plane Intersection or in short TPI.

Keywords: architecture, panelisation, meshing, freeforms

1 Introduction

Hexagonal tessellations of a double curved surface are commonly known. However, apart from the trivial cases like spheres, the polygons contained in these meshes cannot be expected to be planar. The importance and yet even more the pure possibility of planar meshes for architectural applications has moved into the focus of researchers [Liu, Y., Pottmann et al., 2006] and architects only in recent years.

The presented approach has been independently developed and differs from other techniques like the variational shape approximation [Cohen-Steiner et al. 2004] or Cutler and Whiting [Cutler and Whiting 2007] that also produce hexagonal surface panels. The method is neither remeshing a non-planar mesh nor working with a pre-triangulated domain. Instead the basic principle of this technique lies in the intersection of the tangent planes provided by an advancing front mesher that simultaneously places partitions the domain into a generating triangulation and dual planar TPI tessellation.

Generating points are distributed over the domain and provide tangent planes that are intersected with each other. The intersection of one plane with the planes surrounding it will give planar polygonal cell with a side number equal to the number of neighbors. If these neighboring planes are positioned accordingly then it takes at least three intersections to cut a closed cell from the tangent plane, the intersection of two non-parallel planes will yield an intersection line that is lying in both planes. The intersection of this edge with a third plane will generate a 3-valent vertex. The average polygon in the mesh will be hexagonal, yet since it is generated form an unstructured triangular mesh, pentagons heptagons and other polygons are admitted. The flexible topology allows local adaptations and uniform element sizes over the entire domain.

2 TPI related to Gaussian curvature

The shape of the resulting polygon is closely related to the local curvature of the surface. Examining the case of a even arrangement of six points around a central point on different surfaces will give specific results.

In areas of positive Gaussian curvature the hexagons will be convex, yet only in special cases like on a sphere a regular hexagon will form, in areas with anisotropic curvature the polygons will stretch and distort.

A negatively curved surface will give a peculiar result: The polygon becomes non-convex, so that two of its interior angles exceed 180°, giving it a peculiar bowtie-like shape.

In areas of zero curvature like on a cylinder the lateral vertices will align, degenerating the polygon into a rectangle.

Overall there are four classes of panel types in TPI tessellation: The honeycomb in positive, the bow tie in negative curved areas, the degenerate rectangle in single curved areas, and a combination of half honeycomb half bow tie when generating points fall into regions of different Gaussian curvature sign.

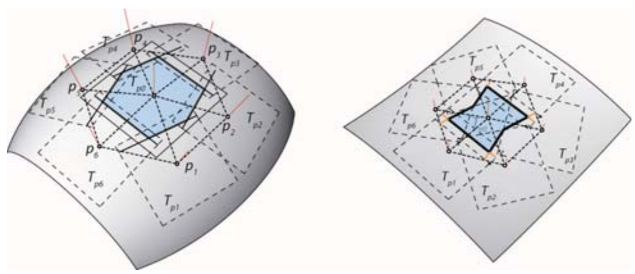


Figure 1: TPI hexagons generated on surfaces of positive and negative curvature.

The bow tie shaped panels may be irritating to the eye of the observer. While the honeycomb like shape is a familiar feature known from many natural phenomena, this shape has hardly any reference in natural structures. This seems to be simple due to the fact, that there is no favoring of planarity in natural processes.

3 Generating triangulations for TPI meshes

3.1. Generator triangulation

A mesh of TPI polygons is based on a dual surface triangulation that connects the generating points of the tangent planes with edges that indicate the adjacency of elements, that is which planes need to be intersected with each other to form the boundary of a TPI polygon. Only those planes contribute that are connected by an generator edge. A generating triangle defines three tangent planes and their intersection gives a vertex of the TPI tessellation.

Therefore the generator mesh is the critical entity for a TPI-tessellation and has to be treated with special attention. This includes two main parameters: The positioning of the nodes and their connectivity.

3.2. Adjacency criterion

For a common Voronoi tiling the empty circle criterion provides an adequate generating Delaunay triangulation [Okabe A. 2000].

Tests have shown that this empty circle criterion is not a suitable tool to determine a correct connectivity of generating points and hence guarantee the creation of valid mesh cells. Non-valid polygons may appear whose boundary is self-intersecting or which is interpenetrating another cell (Figure 2, left).

Though there is no trivial way to check the validity of a generating triangulation beforehand, by reversing the process the validity of panels can be used to evaluate the connectivity of the triangulation:

If the boundaries of adjacent panels show neither interpenetration nor selfintersections, their connectivity mesh is a valid TPI generator mesh.

Interpenetrations and selfintersections generally affect a group of four cells. It can be repaired by a common diagonal edge swap operation that reconnects the points in the generating triangulation (Figure 2, right).

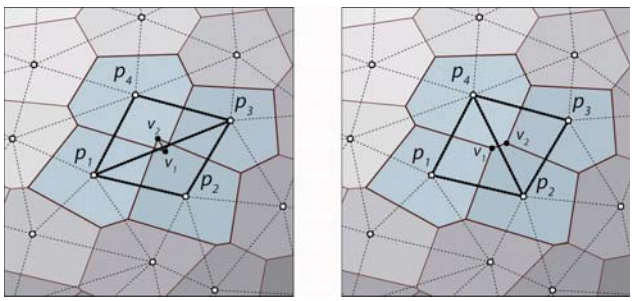


Figure 2: The left configuration shows self-intersection which is repaired by diagonal edge swap on the right.

4 Meshing algorithm for TPI

Still even with this reconnecting edge swap routine not every point set is suited for generating a valid TPI tessellation. On a arbitrary curved surface, even a regular distribution with an even spacing between vertices will generally create a result that is at best unexpected, but commonly it will tend to produce extremely distorted and selfintersecting panels. The problem is less apparent on synclastic shapes with only positive curvature. However on surfaces with both positive and negative curvature and especially in areas with highly anisotropic curvature, the behavior of TPI edges becomes very critical. A well controlled point placement is therefore the most important aspect for a TPI meshing algorithm.

A good meshing algorithm should be capable of covering any arbitrary smooth surface with planar polygons. The basic algorithm used here is an adapted advancing front method. Starting at an arbitrary point inside the domain, the algorithm spreads new triangles whose vertices serve as generator points for tangent plane intersections and subsequently TPI vertices.

On creation the validity of each panel is checked and the location of generating points adapted accordingly.

5 Examination of edge behavior of TPI polygons

The critical question in the advancing front algorithm is where to place new points in relation to the existing triangulation to guarantee a valid and high quality polygon. Tests both on free forms and regular shapes like torus segments have shown that only specific configurations seem to work well and even tiny deviations can produce a huge variation of the results.

To get an insight into this critical behavior a method to visually analyze the orientation of potential edges for a configuration of points is introduced.

The possible edges that a tangent plane on a point of interest can make with a tangent plane from others points a specific distance (the target edge length of the generating triangulation)away are examined. (Figure 3). A full rotation of the potential points around the normal at the investigated point will illustrate the alternation of intersection lines.

Different combination of theses candidates will give potential TPI panels, their vertices defined by the crossings of neighboring edges. The resulting diagrams have a very specific appearance that is closely related to the local curvature of the surface, and also show a surprising aesthetic.

Figure 4 displays the TPI edge maps for different points on a torus surface. The dark blue line is obtained by connecting the points *E* where the edges pass through the normal plane N_0.

While for the positively curved outer region of the torus the edges rotate in a well behaved and constrained manor, they tend to flip in the negatively curved inner part. A generating pair containing points where the edge is almost parallel to N_0 will not be suited to generate a well-behaved TPI mesh. The angle between the edge and the normal plane at p_0 containing p_i should therefore be maximized. Likewise for any point of a sphere it will be 90°.

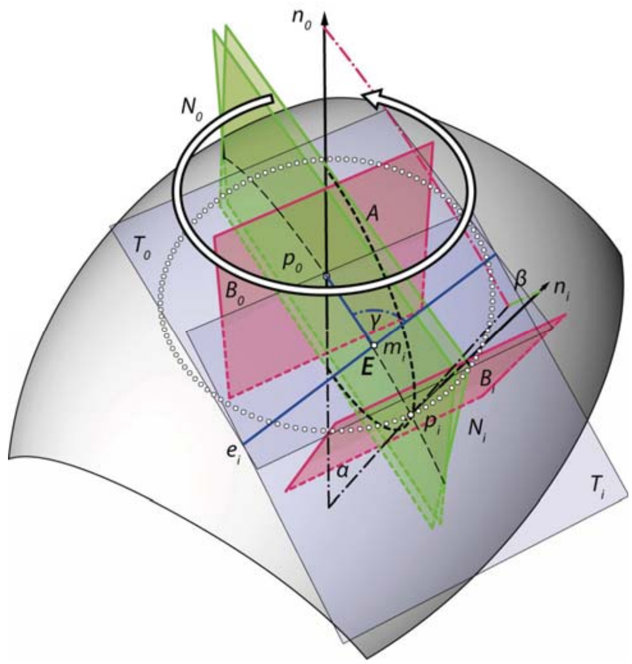


Figure 3: As the Normal plane N0 rotates around the normal n0 the angle a between the N0 and Ni and the angle b between the perpendicular planes B0 and Bi is varying.

While the detailed analysis of the resulting map may be subject to a deeper mathematical research, some important conclusions can be obtained and integrated into the TPIAFT algorithm.

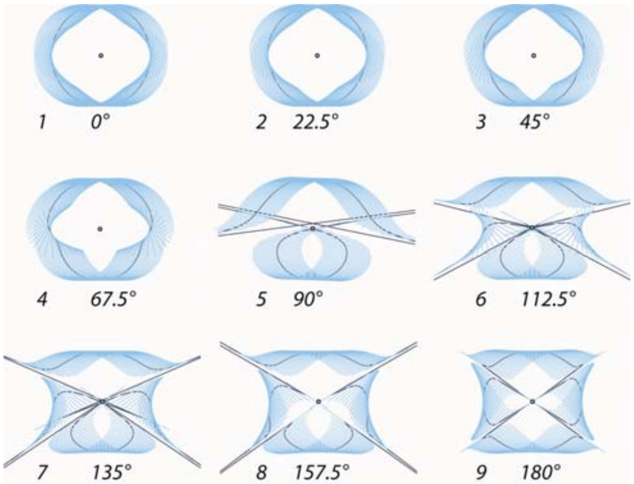


Figure 4: Edge orientation at different position of a torus creates specific patterns.

An ideal edge is perpendicular to the Normal plane, from the graphs of all three angles it can be seen that this happens exactly four times and that this coincides with the angle β between the normal planes being zero. In other words: The normal n_i tilts from one side of the plane to the other and in a special case of β being zero, the normal vectors n_0 and n_i are coplanar, that is, they lie in the same plane.

Of course there is also another term for the angle β and that is the geodesic torsion, and hence ideal edges can be found where the geodesic torsion of the normals of generating points becomes zero, that is both vectors are coplanar.

6 AFT - Algorithms for TPI meshes

6.1. TPIAFT

To regain full control over the TPI-tessellation process, analysis of the point neighborhood is integrated into the point placement procedure controlled by an Advancing Front Technique (AFT) algorithm. The promising concept is that the validity of each generated panel can be evaluated immediately and in the negative case, counter measures can be taken locally to improve the cell. Once a valid cell is created, it will remain unaltered in the tessellation and at the same time, provide a good start for the adjacent cell is shares vertices with.

6.2. Integrating the edge analysis

This algorithm analyses the ideal point pairs for each new panel and sets them accordingly. The edge analysis shows four potential ideal points corresponding to the principal curvature directions, yet for a hexagonal panel two more points are required. Good results have shown for picking the two opposing points corresponding to the minimal principal curvature direction and placing the four lateral points at interpolated positions. This algorithm offers good control over the designated panel size.

6.3. Placing points along Lines of Curvature

It becomes clear that if a sequence of ideally placed TPI panels is arranged in a continous row they follow the surface in a specific pattern. The normal torsion along these lines is minimized and of course these lines are nothing else than the lines of principal curvature along the surface. A promising approach is therefore to locate all generating points along lines of curvature (the lines of minimum curvature specifically.

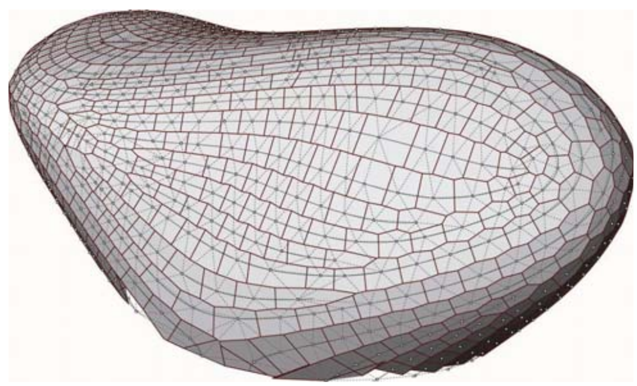
Therefore streamlines of lines of minimum curvature are created on the surfaces and then the panels are distributed along these lines accordingly [Alliez et al. 2005].

The lines of curvatures only serve as guidelines for the point placement. The spacing between points on a line is variable and can be adapted to guarantee uniform panel sizes and edge lengths. Experience shows that in fact the edge length is the most critical issue when transferring the mesh into a material representations. A certain minimal length is dictated by the size of nodes that need to fit on either end of every beam.

6.3.1. Postprocessing

The TPIAFT algorithm while aiming for automation offers various possibilities for interactive manipulations. Single panels can be moved, added to or deleted from the mesh. The topology of the hexagonal mesh is flexible enough to allow locally constrained changes (unlike quadrilateral meshes) together with a rather homogenous element sizes.

Figure 5: Fully meshed surface before postprocessing



7 Architectural Structures from TPI meshes

7.1. Properties of TPI structures

Next to the planarity of the panel element alone there is another important property that implies the great value of these meshes for architectural applications: It is possible to generate a support structure with non-torquing beams and nodes, since the planar hexagonal mesh has a parallel face offset mesh [Liu et al. 2007].

Given the planes defined by an edge vectors and the bisector of the angle enclosed by the corresponding two adjacent panels, the three planes will intersect in a mutual line. This vector can serve as the normal vector for a node element. This seems to be a specific property of all meshes with planar polygons and 3 valent nodes.

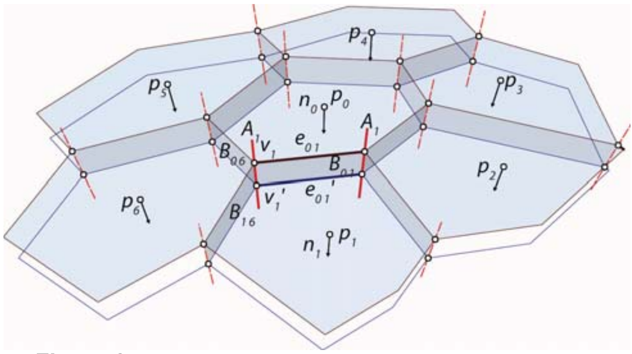


Figure 6: Planar hexagonal TPI mesh with offset mesh and symmetry planes for beam elements and node axis vectors.

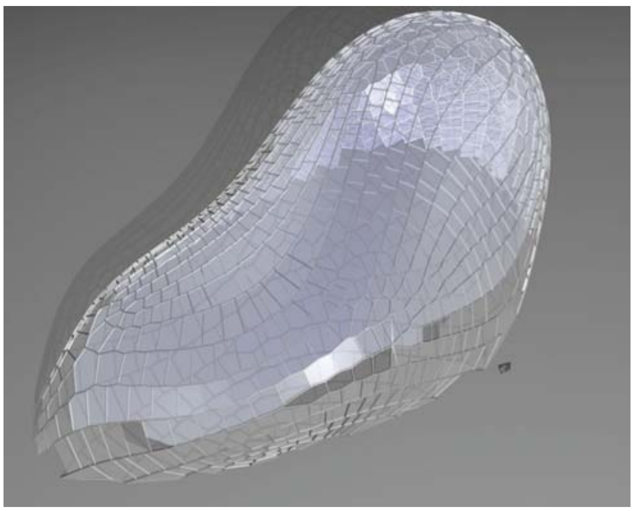


Figure 7: Test design with a non-torquing structure.

7.2. TPI Structure Prototypes

Another focus of research next to the geometric generation of the meshes is their physical realization into prototypic structures. Using CNC controlled 3 axis milling and laser cutting technologies parameter controlled node, beam and panel components can be produced from flat stock material only and assembled to complex 3dimensional surface structures.

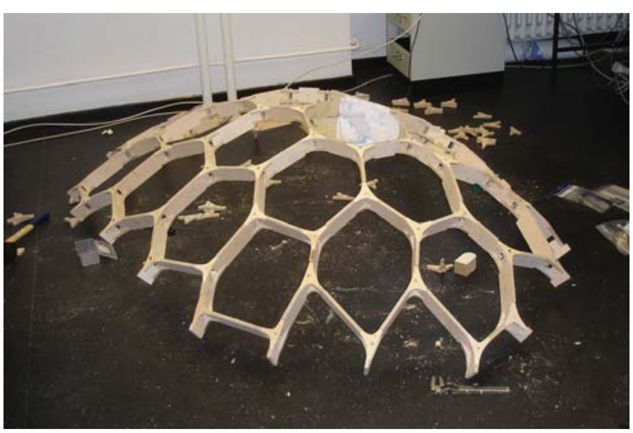


Figure 8: A prototype structure consisting solely of planar CNC cut elements (panels, struts, nodes).

Figure 9: Small and large scale prototypic structures.

Conclusion

Hexagonal TPI meshes offer great opportunities for the architectural structures. While improvements to the algorithm are still necessary they provide the ability to partition any double curved surface into planar panels that can be easily manufactured and assembled in a torsion free structure. The surface itself needs no remodeling and thus the tessellation can give a very close approximation of the smooth original design. Further research is done to speed up the algorithm and improve the panel quality. The flexibility of the method promises far more design possibilities which still wait to be explored.

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On Vertex Offsets of Polyhedral Surfaces

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Abstract

Planar-faced mesh surfaces, also known as polyhedral surfaces, that possess vertex-offsets are useful in architectural design for constructing supporting structures, and also of interest in discrete differential geometry. We consider the existence and computation of vertex-offset meshes of general polyhedral surfaces and, specifically, study how the existence of vertex offsets is dictated by the face shape, mesh surface geometry and mesh surface topology. This extends the study in [Pottmann et al. 2007; Pottmann and Wallner 2008] on vertex-offset meshes of simply-connected circular quad meshes.

Keywords: vertex offset, quasi-circular mesh, mesh parallelism

1 Introduction

Polyhedral surfaces are meshes with planar faces. It has recently been shown [Liu et al. 2006] that polyhedral surfaces, especially those beyond triangle meshes, are useful for modeling glass/metal panels in architectural design. A vertex-offset mesh of a given mesh $\mathcal{M}_0$ is one that has the same mesh connectivity of $\mathcal{M}_0$ and all of its vertices have a same constant distance to their corresponding vertices in $\mathcal{M}_0$. The vertex-offset mesh, along with other variants of offset meshes, are useful for building supporting structures of a building surface modeled as a polyhedral surface [Pottmann et al. 2007].

A circular quad mesh is a mesh with planar quad faces each of which has a circum-circle. Circular meshes were first introduced by Martin et al. [1986] as quad meshes with planar faces which discretize the principal curvature lines of an underlying smooth surface and possess a circum-circle for each quad face. Recently circular meshes have been well studied from the discrete differential geometry point of view [Bobenko and Suris 2005]. The focal geometry of circular meshes, including discrete normals, offsets and focal surfaces, has recently been studied in [Pottmann and Wallner 2008].

A simply connected quad mesh surface possesses a vertex-offset mesh if and only if it is a circular quad mesh [Pottmann et al. 2007]; in fact, a simply connected circular quad mesh has a two-parameter family of parallel spherical meshes [Pottmann and Wallner 2008]. However, the existence of the vertex-offset mesh of a general polyhedral surface is a more complex problem. For example, a quad mesh with more than one closed boundaries or a closed quad mesh with nonzero genus may not have vertex-offset meshes, except for the trivial case of a translation of the mesh. Two examples are shown in Figure 1.

We study in this paper how the existence of vertex-offset meshes of a polyhedral surface is governed by the face shape, mesh surface geometry and mesh surface topology. We also present numerical techniques for computing the parallel spherical meshes of a vertex-offset mesh.

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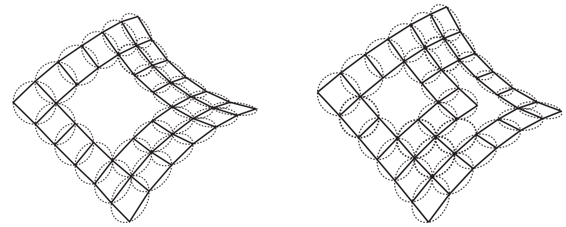

Figure 1: *Both quad meshes are circular meshes. The one on the left has a unique parallel spherical mesh, and the one one the right has no parallel spherical mesh and therefore no vertex offset.*

2 Quasi-circular polygons and meshes

The vertex offset can be characterized using the concept of parallel meshes [Pottmann et al. 2007] – a mesh $\mathcal{M}_0$ possesses a vertex-offset mesh if and only if it has a parallel spherical mesh $\mathcal{M}_s$, which is a mesh that has all of its vertices lie on the unit sphere S^2. Such a mesh $\mathcal{M}_s$ is called a parallel spherical embedding mesh of $\mathcal{M}_0$. Based on this result, our study will be centered around the existence of the spherical embedding meshes of a given mesh. We first introduce necessary notions and definitions.

A mesh $\mathcal{M}$ is a *planar polygonal mesh*, or called *a polyhedral surface*, if every face of $\mathcal{M}$ spans a plane. Since we always require face planarity, all meshes discussed in the paper will be assumed to have planar faces. A *proper mesh* is one such that it does not have degenerate edges, that is, the two endpoints of any edge are not identical.

Two polygons are *parallel* if their vertices can be put in one-to-one correspondence such that the corresponding edges are parallel. A *circular polygon* is a planar polygon inscribed in a circle. A *circular mesh* is a mesh all of whose faces are circular polygons. To study the vertex-offset mesh of a general mesh in the framework of parallel meshes, we need to go beyond circular meshes.

Definition 1 *A planar polygon $\mathcal{P}$ is called a* quasi-circular polygon *if it has a parallel non-degenerate circular polygon $\mathcal{P}_c$ inscribed in a unit circle S^1. Here the non-degeneracy of $\mathcal{P}_c$ means that if the two endpoints u_c and v_c of any edge e_c of $\mathcal{P}_c$ are identical, then the direction of e_c's corresponding edge e in $\mathcal{P}$ is tangent to the circle S^1 at u_c $(= v_c)$. We call $\mathcal{P}_c$ a* circular embedding polygon *of $\mathcal{P}$.*

Note that any triangle is circular, since it has a unique circum-circle. A planar quad is circular if the sums of two opposite internal angles are equal. A quasi-circular quad mesh $\mathcal{P}$ has infinitely many circular embedding polygons, including itself; therefore, a quasi-circular quad is also circular. However, a quasi-circular polygon with more than four sides, in general, is not circular.

Definition 2 *A mesh is called a* quasi-circular mesh *if all of its faces are quasi-circular polygons.*

The notion of quasi-circular meshes is the equivalent to that of circular meshes for quad meshes, but different from and more general than the latter for mesh faces that contain faces with more than four sides.

Two polygonal meshes are defined to be *parallel* if their vertices are in one-to-one correspondence with isomorphic edge connectivity and their corresponding edges are parallel. Clearly, the corresponding faces of two parallel meshes are parallel.

Definition 3 *A mesh is a* spherical mesh *if all of its vertices lie on the unit sphere* S^2.

The existence of the vertex-offset meshes of a given mesh can be characterized by the existence of its parallel spherical meshes, as observed in [Pottmann et al. 2007]. This is summarized as follows.

Proposition 1 *A mesh $\mathcal{M}$ has a vertex-offset mesh if and only if it has a non-degenerate parallel spherical mesh $\mathcal{M}_s$. Here a "non-degenerate" $\mathcal{M}_s$ means that if the two endpoints u_s and v_s of any edge e_s of $\mathcal{M}_s$ are identical, then the direction of e_s's corresponding edge e in $\mathcal{M}$ is parallel to the tangent plane of S^2 at u_s $(= v_s)$.*

We also call $\mathcal{M}_s$ the parallel spherical embedding of $\mathcal{M}$. With $\mathcal{M}_s$, a vertex-offset mesh $\mathcal{M}_o$ of $\mathcal{M}$ can be expressed as $\mathcal{M}_o := \mathcal{M} + d\mathcal{M}_s$, for some constant d and "+" is vector addition applied to the coordinates of the corresponding vertices. By insisting on the non-degeneracy of $\mathcal{M}_s$, we have excluded the trivial case where $\mathcal{M}_o$ is a translational copy of $\mathcal{M}$, which would be caused by $\mathcal{M}_s$ collapsing into a single point on S^2.

It follows from Proposition 1 that a mesh possessing a vertex-offset mesh is a quasi-circular mesh. This conditions turns out to be also sufficient for a simply connected circular quad mesh, as pointed above, since a simply connected circular quad mesh always has a two-parameter family of parallel spherical meshes [Pottmann and Wallner 2008].

We now consider the 2D reflections induced by the sides a quasi-circular polygon $\mathcal{P} : \mathrm{u}_0\mathrm{u}_1 \cdots \mathrm{u}_n$, with $\mathrm{u}_0 = \mathrm{u}_n$. Similar to the procedure described in Remark 11 in [Pottmann and Wallner 2008], the construction of a circular embedding polygon $\mathcal{P}' : \mathrm{u}'_0\mathrm{u}'_1 \cdots \mathrm{u}'_n$ of $\mathcal{P}$ can be obtained via a series of reflections. The procedure is as follows:

- Pick a point u'_0 on the unit circle, set $j = 0$;
- Repeat the following procedure until $j = n$: Select the line passing through the origin and orthogonal to $\overrightarrow{\mathrm{u}_{j+1}\mathrm{u}_j}$ as the reflection line. Reflect u'_j in this line to obtain u'_{j+1}. (This reflection is denoted as T_j which is a 2×2 orthogonal matrix.) Set $j := j + 1$.

If $\mathcal{P}$ is a quasi-circular polygon, then there needs to be $\mathrm{u}'_0 = \mathrm{u}'_n$ in order for $\mathcal{P}'$ to exist. Define $T_{\mathtt{ref}} := T_{n-1} \circ T_{n-2} \circ \cdots \circ T_1 \circ T_0$. Then $\mathrm{u}'_0 = \mathrm{u}'_n$ implies $\mathrm{u}'_0 = T_{\mathtt{ref}}\mathrm{u}'_0$, or equivalently, $T_{\mathtt{ref}}$ has an eigenvalue equal to 1 and u'_0 is the associated eigenvector. Since each reflection T_j is a 2×2 orthogonal matrix with $\det(T_j) = -1$, $T_{\mathtt{ref}}$ is orthogonal with $\det(T_{\mathtt{ref}}) = -1$ when n is odd and $\det(T_{\mathtt{ref}}) = 1$ when n is even.

When n is odd, the two eigenvalues of $T_{\mathtt{ref}}$ are 1 and -1. That is to say, there is a unique invariant vector u'_0 of $T_{\mathtt{ref}}$ in this case, up to scaling. Hence, there are exactly two circular embedding polygons of $\mathcal{P}$, given by a unit invariant vector u'_0 of $T_{\mathtt{ref}}$ and $-\mathrm{u}'_0$. We state this as a proposition.

Proposition 2 *Any odd-sided planar polygon is a quasi-circular polygon with two circular embedding polygons, which are reflections of each other about the center of the circle.*

When n is even, it is easy to see that $T_{\mathtt{ref}} = I_{2\times 2}$ (the identity matrix) if and only if $\mathcal{P}$ is quasi-circular. In this case, any point u'_0 on the unit circle S^1 gives an eigenvalue vector of $T_{\mathtt{ref}}$; therefore, there is a one-parameter family of circular embedding polygons of $\mathcal{P}$. When n is even and $\mathcal{P}$ is not quasi-circular, the eigenvalues of $T_{\mathtt{ref}}$ are complex conjugate or -1 and -1, representing a 2D rotation of angle not equal to a multiple of 2π.

A quasi-circular even-sided convex polygon is characterized by the following theorem (we do not include its proof here due to space limit).

Theorem 1 *An even-sided planar polygon $P = \mathrm{u}_1\mathrm{u}_2 \ldots \mathrm{u}_{2n}$ is a quasi-circular if and only if its internal angles $\theta_1, \theta_2, \ldots, \theta_{2n}$ satisfy $\theta_1 + \theta_3 + \ldots + \theta_{2n-1} = \theta_2 + \theta_4 + \ldots + \theta_{2n}$.*

Proposition 3 *An even-sided quasi-circular polygon has a one-parameter family of circular embedding polygons.*

Consider a quasi-circular (planar) polygon in 3D. The reflections along its successive sides define a series of reflections in 3D following a similar procedure: we reflect the vertex u'_j with respect to the plane with normal vector $\overrightarrow{\mathrm{u}_{i+1}\mathrm{u}_i}$ which passes through the origin to obtain u'_{j+1}. All possible combinations of the eigenvalues of $T_{\mathtt{ref}}$ are listed in the following table.

A quasi-circular polygon in 3D	$\det(T_{\mathtt{ref}}) = 1$ (n is even)	$\det(T_{\mathtt{ref}}) = -1$ (n is odd)
Eigenvalues	$\{1, 1, 1\}$	$\{1, 1, -1\}$

It follows that an even-sided quasi-circular polygon $\mathcal{P}$ has a two-parameter family of parallel embedding polygons on the unit sphere S^2; in this case any point on S^2 can be used as a starting point u'_0 to construct an embedding $\mathcal{P}'$ of $\mathcal{P}$ on S^2. For an odd-sided planar polygon, which is always quasi-circular (cf. Proposition 2), there is a one-parameter family of parallel embedding polygons on S^2. In this case, the initial point u'_0 of $\mathcal{P}'$ is confined to be on a great arc of S^2. Hence, we conclude that if a mesh $\mathcal{P}$ contains more than two odd-sided faces in general orientations, then $\mathcal{P}$, in general, does not have a parallel spherical embedding and therefore has no vertex-offset meshes, since three great circles on S^2, in general, do not have a common point.

This suggests that meshes with odd-sided faces, such as triangle meshes and pentagonal meshes, are not amendable to vertex-offset computation. Hence, from now on we will only consider quasi-circular meshes with even-sided face, which will be referred to as a *quasi-circular even-sided polygonal mesh*, or *QCEP mesh* for short.

3 Spherical loops and loop homotopy

A quasi-circular mesh is characterized by the local condition that each face is quasi-circular. Except in the case of a simply connected quasi-circular mesh, the existence of the vertex-offset of a general quasi-circular mesh is determined globally by the shape and topology of the mesh. Here, the topology refers to the number of closed boundaries for an open mesh surface and the genus for a closed mesh surface. To study this topological aspect, we need to consider loops on the mesh.

A *loop* $\mathcal{L}$ on a mesh $\mathcal{P}$ is a closed path consisting of a sequence of incident edges of $\mathcal{P}$; therefore, it is, in fact, a closed polygon in 3D, which is not necessarily planar. Parallel loops are defined in the same way as for parallel planar polygons. All loops on a mesh surface can be classified into equivalence classes via homotopy – two loops are homotopic if they can deform continuously into each other on the surface. Evidently, a loop $\mathcal{L}_1$ on a quasi-circular EP mesh $\mathcal{P}$ can be deformed into another loop $\mathcal{L}_2$ homotopic to $\mathcal{L}_1$ via a sequence of face addition or face removal operations, one face at a time.

Definition 4 *A loop $\mathcal{L}$ is* quasi-spherical *if it has a non-degenerate parallel loop $\mathcal{L}'$ whose vertices are on the unit sphere S^2. Here a "non-degenerate" parallel loop $\mathcal{L}'$ means that if the two endpoints u_s and v_s of any edge e_s of the parallel loop $\mathcal{L}'$ are identical, then the direction of e_s's corresponding edge e in $\mathcal{L}$ is parallel to the* *tangent plane of S^2 at u_s $(= v_s)$. The loop $\mathcal{L}'$ is called a* parallel spherical embedding loop *of $\mathcal{L}$.*

The next theorem implies that if a loop on a quasi-circular mesh is quasi-spherical, then all loops homotopic to it are quasi-spherical. We skip the proof due to space limit.

Theorem 2 *Suppose that $\mathcal{L}_1$ and $\mathcal{L}_2$ are homotopic on a quasi-circular even-sided (QCEP) mesh $\mathcal{P}$. Then $\mathcal{L}_1$ is quasi-spherical if and only if $\mathcal{L}_2$ is quasi-spherical. Furthermore, when $\mathcal{L}_1$ is quasi-spherical, all the parallel spherical embedding loops of $\mathcal{L}_1$ are consistent and in one-to-one correspondence with those of $\mathcal{L}_2$.*

Clearly, any loop on a mesh which has a parallel spherical embedding is quasi-spherical. Therefore, if there is a non-quasi-spherical loop on a quasi-circular mesh, then the mesh does not have a vertex-offset mesh.

A loop induces a sequence of 3D reflections along it sides. Whether or not a loop is quasi-spherical can be analyzed by considering the eigenvalues of the composition of the reflections, again denoted as $T_{\texttt{ref}}$. All possible combinations of the eigenvalues of $T_{\texttt{ref}}$ for an n-sided loop in 3D are listed in the following table.

A loop in 3D	$\det(T_{\texttt{ref}}) = 1$ (n is even)	$\det(T_{\texttt{ref}}) = -1$ (n is odd)
Eigenvalues	$\{1, 1, 1\}$ $\{1, -1, -1\}$ $\{1, a + b\mathbf{i}, a - b\mathbf{i}\}$	$\{1, 1, -1\}$ $\{-1, -1, -1\}$ $\{-1, a + b\mathbf{i}, a - b\mathbf{i}\}$

Here $a^2 + b^2 = 1, a, b \neq 0$ and $a, b \in \mathbb{R}$.

Hence, an even-sided loop is always quasi-spherical, since $T_{\texttt{ref}}$ has at least one eigenvalue equal to 1. In the special case where the eigenvalues are $\{1, 1, 1\}$, the loop has a two-parameter family of parallel spherical embedding loops. An odd-sided loop may not be quasi-spherical, since it may not have an eigenvalue equal to 1. Only in the special case where the eigenvalues are $\{1, 1, -1\}$, the loop has a one-parameter family of parallel spherical embedding loops; this happens, for instance, for an odd-sided planar polygon.

4 Existence of vertex-offset meshes

Open quasi-circular meshes For a simply connected open QCEP mesh, all loops on it are simply connected, even-sided, and homotopic to each other. In particular, every loop is homotopic to every face of $\mathcal{M}$, which is even-sided and quasi-circular with a two-parameter family of spherical embedding polygons. Hence, any simply connected QCEP mesh has a two-parameter family of parallel spherical embedding meshes.

Now consider an open QCEP mesh $\mathcal{M}$ with one hole, which has the topology of a truncated cylinder, as shown for example in Figure 1 (left). Clearly, a simply connected loop $\mathcal{L}_0$ on $\mathcal{M}$ is even-sided, but a non-simply connected loop $\mathcal{L}_1$ around the hole (with winding number equal to 1) may be even-sided or odd-sided. If $\mathcal{L}_1$ is even-sided, then $\mathcal{L}_1$ is quasi-spherical and there are in general two parallel spherical meshes of $\mathcal{L}_1$ that are reflections of each other about the center of the sphere, resulting from a unit invariant eigenvector u_0' of $T_{\texttt{ref}}$ and $-\mathrm{u}_0'$; two such spherical meshes are said to be *diametrically opposite*, and they lead to the unique family of vertex offset meshes $\mathcal{M}_o := \mathcal{M} + d\mathcal{M}_s$ with the parameter d. It follows that the mesh $\mathcal{P}$ in general has a unique vertex-offset mesh, since any other loop around the hole as an element of the fundamental group of $\mathcal{M}$ can be generated from the generators $\mathcal{L}_0$ and $\mathcal{L}_1$. In the special case where $T_{\texttt{ref}} = I_{3\times 3}$ for $\mathcal{L}_1$, $\mathcal{M}$ has a two-parameter family of parallel spherical meshes. When $\mathcal{L}_1$ is odd-sided, $\mathcal{M}$ in general does not have a vertex-offset mesh.

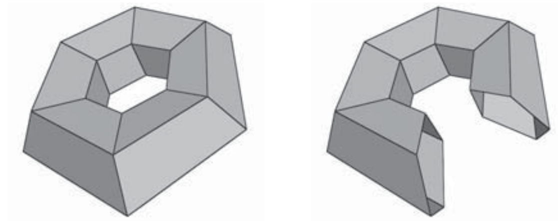

Figure 2: *A torus-like QCEP mesh without a vertex-offset mesh (left). The same surface but with one row removed for better illustration.*

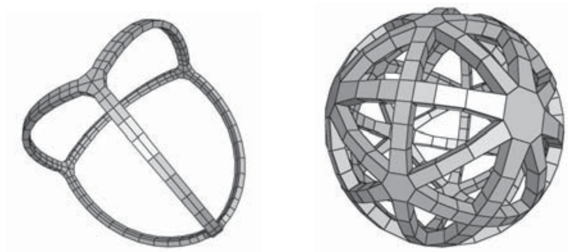

Figure 3: *Two QCEP meshes without vertex-offset meshes. The one on the left has non-homotopic quasi-spherical loops whose parallel spherical embedding loops are inconsistent with each other. The one on the right has odd-sided loops that are not quasi-spherical. The original models are from the repository of TOPMOD.*

When an open QCEP mesh $\mathcal{M}$ has more than one hole, there are at least three closed boundary loops that are not homotopic to each other. Then $\mathcal{M}$ in general does not have any vertex-offset mesh, even if each loop is quasi-spherical, since the spherical embedding loops of these loops may not have a common vertex.

Closed quasi-circular meshes The topology of a closed QCEP mesh is indicated by its genus, i.e., the number of its handles. First, if a QCEP mesh $\mathcal{M}$ is a topological sphere, then it is simply connected. Consequently, we can show that it has a two-parameter family of vertex-offset meshes.

For a QCEP mesh $\mathcal{M}$ of genus 1 or higher, there are at least three loops that are mutually non-homotopic. It follows that $\mathcal{M}$ in general does not has a vertex-offset mesh, either because one of these loops is not quasi-spherical or because the parallel spherical embedding loops of these non-homotopic loops are inconsistent even if they are all quasi-spherical. Figure 2 shows a QCEP mesh that does not have a vertex offset, because it contains a non-planar odd-sided loop that is non-quasi-spherical. Figure 3 shows two more QCEP meshes with high genus that have no vertex-offset meshes.

For a closed QCEP mesh $\mathcal{M}$ of genus $g > 0$, if all the generator loops of the fundamental group of $\mathcal{M}$ are even-sided, quasi-spherical and have their composed reflections $T_{\texttt{ref}} = I_{3\times 3}$, then $\mathcal{M}$ has a two-parameter family of spherical meshes, and hence a two-parameter family of vertex offsets.

Finally, the above observations also apply to a QCEP mesh surface with open boundaries and handles.

5 Numerical computation of parallel spherical meshes

In the preceding sections we considered the existence of parallel spherical meshes of a quasi-circular mesh via an analysis of mesh topology. Checking whether each loop is quasi-circular is not an

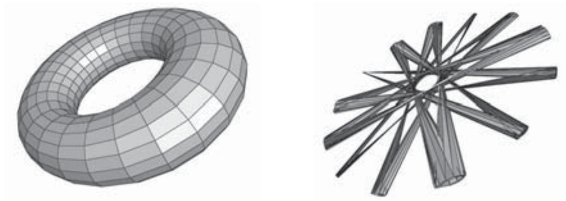

Figure 4: *A torus-like circular quadrilateral mesh (left) with its unique parallel spherical mesh (right).*

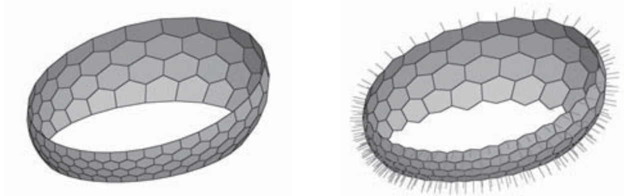

Figure 5: *Left: A hexagonal mesh before optimization; right: A quasi-circular hexagonal mesh after optimization with its discrete normal.*

efficient way to determine the existence of the parallel spherical mesh. In this section, we utilize mesh parallelism and reflectional properties to compute the basis of the parallel spherical mesh.

Denote a given quasi-circular polygonal mesh as $\mathcal{M}$ and its parallel spherical mesh be denoted as $\mathcal{M}_s$. Denote the edges of $\mathcal{M}$ and $\mathcal{M}_s$ as e_k and e'_k, $k = 1, \ldots, N_e$. The two end vertices of e_k and e'_k are denoted as $\mathrm{v}_{k,1}, \mathrm{v}_{k,2}$ and $\mathrm{v}'_{k,1}, \mathrm{v}'_{k,2}$, respectively. Since the corresponding edges of $\mathcal{M}$ and $\mathcal{M}_s$ are parallel, we have

$$(\mathrm{v}_{k,2} - \mathrm{v}_{k,1}) \times (\mathrm{v}'_{k,2} - \mathrm{v}'_{k,1}) = \mathbf{0},\ k = 1, \ldots, N_e, \qquad (1)$$

where "$\times$" stands for vector vector cross-product in 3D. Since $\mathrm{v}'_{k,1}$ and $\mathrm{v}'_{k,2}$ on S^2 are related by a reflection in a plane with the normal vector $\mathrm{v}_{k,2} - \mathrm{v}_{k,1}$, we have

$$\frac{\mathrm{v}'_{k,1} + \mathrm{v}'_{k,2}}{2} \cdot (\mathrm{v}_{k,2} - \mathrm{v}_{k,1}) = 0,\ k = 1, \ldots, N_e, \qquad (2)$$

where "$\cdot$" stands for inner-product. Note that the last equation also ensures the non-degeneracy of $\mathcal{M}_s$ with respect to $\mathcal{M}$ when $\mathrm{v}'_{k,1} = \mathrm{v}'_{k,2}$ (cf. Proposition 1). Thus we obtain a homogenous sparse linear system with size $4N_e \times 3N_v$, where N_v is the number of vertices and v' are unknowns. The space of the vertices of $\mathcal{M}_s$ is the null space of the sparse system of the linear equations, which can be solved by SVD efficiently. Figure 4 shows an example.

Meshes produced from architects are often not circular, and not even planar, in general. If one wishes to compute a vertex offset mesh of such a mesh, one may use the numerical optimization technique presented in [Liu et al. 2006; Pottmann et al. 2007]. For meshes with even-sided faces, face quasi-circularity can be attained with optimization based on the condition of equal angle sums as stated in Theorem 1. (For reasons stated previously, we will not consider here circular meshes with odd-sided faces.) For example, using the optimization technique similar to that presented in [Liu et al. 2006; Pottmann et al. 2007] via mesh vertex perturbation, one can turn a given hexagonal mesh into a quasi-circular planar hexagonal mesh by enforcing $\sum_{i=1}^{6} \theta_i = 4\pi$ (face planarity) and $\theta_1 + \theta_3 + \theta_5 = \theta_2 + \theta_4 + \theta_6$ (quasi-circularity) for each face. An example is shown in Figure 5.

Based on Theorem 1 and our numerical optimization technique, we can also handle a quasi-circular mesh with mixed types of faces. For example, Figure 6 shows a simply connected QCEP mesh with

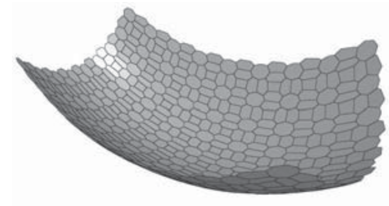

Figure 6: *A QCEP polygonal mesh with three types of faces – quadrilateral, hexagonal and octagonal faces. This mesh also possesses a face-offset mesh, since each of its interior vertices has valence 3.*

three types of quasi-circular faces. This mesh has a two-parameter family of vertex-offset meshes.

6 Conclusion and future research

We have studied the vertex-offset meshes of general polygonal meshes and show how their existence is dictated by face shape, surface geometry and surface topology. Our analysis is based on parallel spherical meshes, eigenvalue analysis of reflection transformations, and loop homotopy. We have provided an optimization method for computing the parallel spherical mesh of a given mesh, when it exists.

Further research problems include the following:

- The success of optimization methods for achieving face planarity depends strongly on initialization. It is well known that a circular quadrilateral mesh discretizes the principal curvature lines, so the initialization of a circular quad mesh should come from an appropriate sampling of the curvature lines. But for a general polygonal mesh, there is lack of research on how to go about this initialization.
- Due to aesthetic reasons, an open mesh from architecture design may have holes, which causes problems for computing vertex-offset meshes. One possible solution under investigation is to first fill the holes with EP meshes to make the mesh simply connected and then perform quasi-circular optimization and obtain the basis of parallel spherical meshes for computing discrete normal and offset structure. After that, the filled parts can be removed to restore the structure of the original the holes.

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Complex geometries in Wood

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Abstract

The versatility of wood constructions and traditional wood joints for the production of non standard elements was in focus of a design based research. Herein we established a seamless process from digital design to fabrication. A first research phase centered on the development of a robust parametric model and a generic design language a later explored the possibilities to construct complex shaped geometries with self registering joints on modern wood crafting machines. The research was carried out as collaboration with industrial partners.

Keywords: Digital production, CAD/CAM, Parametric design, complex form, mass customization, industry cooperation, design research, Case study

Figure 1: 1:1 prototype showcasing the potential of wood joints for non standard element architecture

1 Design Research

In his book "The Projective cast" Robin Evans (1995) points out how the development of techniques changed architecture and the space inhabited in times of Gothic and early Renaissance. Today a similar change due to the adoption of computational techniques into architectural design can be observed. The yields of digital design techniques are accompanied by a further dissolution of the link between concept, shape and production, a phenomenon Michael Speaks (2000) calls the "Dimishing of connection between form and ideology". Whereas the computation of geometry proceeds in design on fast pace using relational geometry the later construction and production does not pick up digital opportunities to the same extend.

This is remarkable as building industry and the crafts have invested heavily in digital machinery and processes in order to increase productivity. But equally to the field of architecture new techniques resemble primarily the traditional production processes. Seamless digital workflows between the partners in the building process could enable the construction of more complex geometries using non standard elements for the build; this especially as the machinery in small and midsized craft related companies bear a high versatility.

2 Wood and joints

Wood is generally considered as one of the most sustainable building materials. It as well is connected to an enormous range of different ways of processing and joining. Especially the ability to easily process the joint directly from the material itself is remarkable. “The benefits of components with integrated attachments geometry are that the attachments can be designed and controlled as part of the generative process” as Larry Sass (2006) states . Based on a long tradition in the crafts wood-wood joints, especially those based on friction as dovetail joints, have advantages:

- Can be specific to certain geometrical and tectonic requirements
- Monolithic setup allows unrestricted movement
- Inherit tolerance
- High level of prefabrication
- Efficiency in assembly due self registering joints and little or less secondary elements, as screws or bolts

Precedent research has shown the advantage of implementing self registering joints that can adapt geometrically to specific local requirements in the construction (Holzner 1999, Kilian 2003, Schindler 2007). The required production capacity is given in modern highly flexible CNC wood joinery machines. They enable not only the very fast production of individualized wooden beams but as well the rational production of geometrical complex individual joints that fit with little tolerances.

Usually material and machining costs are not the main factor in the fabrication of constructions- labor, production and transport are at most equally important (Westney 1997). The easy assembly of elements due to the interplay of high precision and almost total prefabrication due to CNC manufacturing and the easy assembly of elements with self registering joints reduce the costs for complex constructions in wood. Geometrical almost unrestricted joints should furthermore enable new ways of design.

3 Repetition and Series

As modern techniques allow for mass customization, the focus of design shifts from the constitution of a solution (i.e. single elements), that already has the final overall output in terms of geometry and internal distribution of functions imbedded, towards the definition of relationships between the elements in play. Herein the difference between the elements informs a possible final geometry. As the constitution of every element may varies the formulated overall geometry is just one out of many – solely defined by the given parameters and the setup of the internal rules of interaction, which becomes the main design task . The evolving systems oriented on a Deleuzian (Keith Ansell-Pearson 1999) understanding allow new ways to think design. It allows for the easy exploration of a multitude of design solutions. Herein the momentum of series becomes a crucial part as it chances for evolution and adaption to different states. The drawing of difference within the series can result in gradual as well as sudden shifts. Yet unlike classical products of mass customization, as first seen within the work of Artists as Andy Warhol (Collings 1998) or nowadays in customer products (Reebok 2008), the elements in our design setup are not solely changing properties but topology. In addition to the examination of change over time, represented in the diagrammatic linear alignment as in the mapping of different states of an object due to movement of its parts, first examined by Eadweard Muybridge (Clegg 2007) and Étienne-Jules Marey (1890), we introduced topological change and its infliction with the designs overall appearance. So the appearance of internal spaces, poche and openings became a strong moment within our design exploration.

4 Design Concept

Starting from a real building project – the façade of a large scale multi storey Parking lot, wherein a parametric concept using CNC wood manufacturing processes was proposed (Design: Martin Tamke and Blunck & Morgen Architects Hamburg) – the research project looked at ways to explore the link between design intent, formal and special expression and the realization process.

Fig.2: Initial Design Concept: a series of kinked beams create an overall surface with changing transparencies and patterns. The diagram shows possible sections through the construction shown in the rendering on the right.

The basic idea of the design, as shown in fig.2, consisted of evenly divided but differently kinked beams. Looking at the overall series appearance wavelike patterns with changing transparencies and densities appear, when ever the observer moves along the facade.

5 Design of Parametric Model

First investigations of the design showed that it could be easily transferred into a parametric model based on the structures axis system. As the concept consisted of only a few determining parameters it could serve as a well-defined starting point for further geometrical experimentation. The parametric model itself consisted of three nested interacting levels with individual sets of parameters:

- Basic layout of rails and distribution of beams
- Beam structure (represented by mid axis)
- Solid shape

The parametric model not only allowed a direct link to production in the very first design process due to the embedding of fabrication specific parameters but as well the exploration of several variations within the design until certain predefined or evolving performance parameters were met. These parameters were later defined by tectonic, material, fabrication and aesthetic considerations. The exploration was conducted in an iterative process. Every design iteration led to a physical scale model, whose constituting elements and emerging nature could be discussed. These were distilled and emphasized in the next generation of models. By doing so a individual design language could be established.

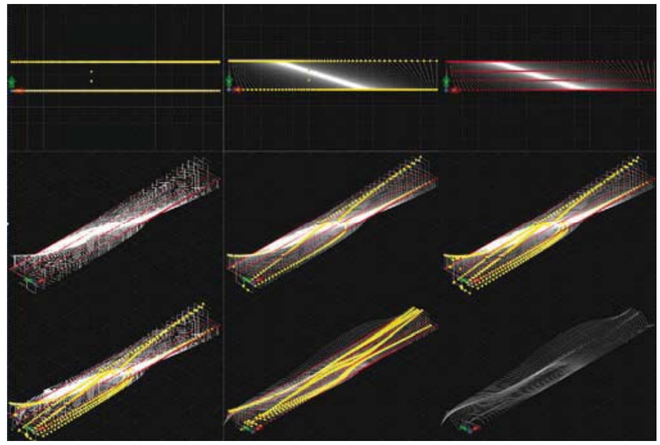

Fig.2: Setup of the parametric system from basic layout of the guiding rails and axis systems to solid shape representation.

5.1. Interfacing - Control of the system

With a view to an intuitive handling (Burry 2005) the systems control via diagrammatic representations showed good results (called law curves in the tools underlying software package Generative Components). Whereas first models showed a direct and foreseeable reaction to changes of parameters, later ones with more and interdependent parameters showed more complex behavior. This led to the design of an abstract second order representation of the parameter driving law curves. This deflection showed good results, counterfeiting the fact that the addressing of specific areas and phenomena within the model became harder to predict the more parameters were in play.

Fig.3: Laser cut wood model directly processed from Fig 2 parametric system

5.2. Internal behavior

Being able to address the overall composition and inter-element behavior of the design as well as the internal properties and geometrical setup of every element offered a wide range for manipulation, such as dimension and kink. In the course of the process further shifts were introduced, i.e. amount of members, tilt, density, spacing and creasing. Branching led to desired topological change. Several design iterations proved the robustness of the chosen parametric model. Yet vast amounts of internal calculations limited interactivity. This especially in the last step, when overall geometric freedom was introduced and the formerly straight carrying rails, were transformed into three-dimensional bending curves – creating massive topological change within the series.

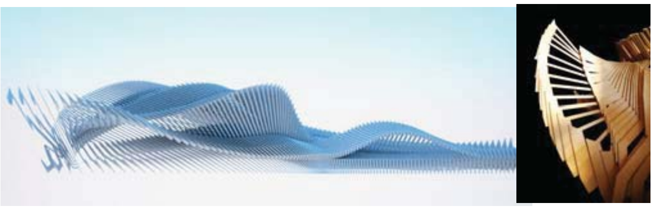

Fig.4: Rendering and wood model of the designs last level

5.3. Joints

The geometric freedom demanded the invention of versatile but yet geometrically precise joints that could be produced by the 2D laser cutting technology available. Internal measurements informed the placement and dimension of joining points. Due to the high precision of digital fabrication and embedded tolerance the beams, meeting the adjacent rails in ever changing angles could be easily plugged in.

Derived parameters from internal calculations served well in the later 1:1 demonstrator.

6 Demonstrator

Whereas the experiments in model scale served well for the setup of a parametrical design to production line and the establishment of an overall design language the scaling to an architectural scale and the operation on CNC wood joinery machinery formulated the last step in the process and a prove of concept.

6.1. Evolution of parametric model

Solid beams and 3 dimensional shaped geometries required more control. Therefore algorithms constructing the final geometries in real-time according local conditions have been introduced.

6.1.1. Generation of 2nd order geometry

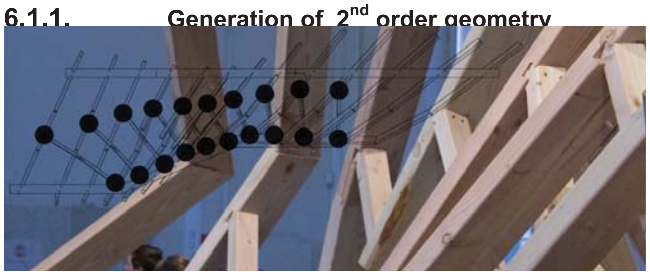

Fig. 5. Places of diagonal beams: example of automatically generated 2nd order geometry.

In order to increase the stability of the construction diagonal beams were introduced connecting non adjacent beams. Which members met where and under which angle could be adjusted parametrically. The final second order geometries derived from the given local status of the involved members.

6.1.2. Shifting beams

Another feature introduced was the shift of beams from one side of the structure to the other. In contrast to the initial Parking Lot project, the rails can swing now in both directions. The combination with the rails own curving created openings and pockets.

6.1.3. Solver algorithms

As the underlying parametric model was based on an abstract axis system the implications with material thickness had to be taken into account. For example a solver algorithm, courtesy provided by Axel Kilian, was used, which iteratively shifted the depth of the cutout between rail and beam towards a given optimal value.

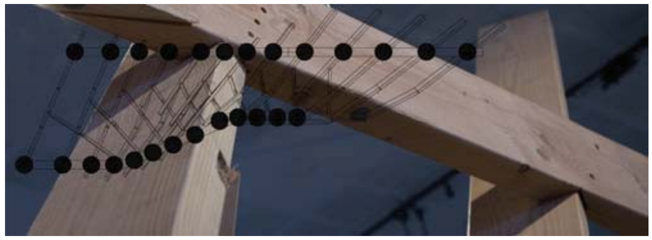

Fig. 6: Automatic calculation of cutouts by solver algorithms

6.2. Workflow and production parameters

The development of the process focused on a smooth functioning and seamless workflow. Thus we tried to use as much existing tool as possible and test their capacity before writing proprietary tools. Such as the Wood CAM tool HSB Cad, this could easily read our data. Its function was to define the different wood-joints on the predefined beam structure and write instructions for the wood joinery machine. A color-code modeler eased the identification of beams and the application of different craft based joints, as notches, cuts, dovetails and rafter joints.

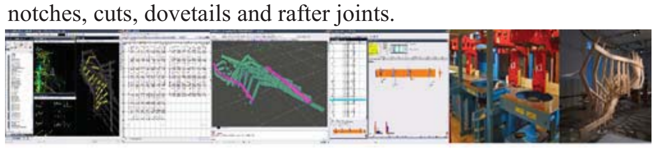

Fig.7: Fabrication process from the parametric geometric model, along the control and application of joints to the CNC machinery

As the CAM program used has no build in plausibility check – not producible wood operations could be send from the parametric modeler to the machine driving program - it was necessary to integrate the machines limitations into the parametric model (i.e Tools and wood dimensions).Others had to be detected in an iterative process. Thanks to the parametric setup this process took just a few hours at the factories site.

This requirements were represented within the parametric model either by algorithms limiting certain values or by the real-time update of measured values in an excel sheet. The constant control of the values by the designer served i.e. well for the control of the minimal length of beams, as too many interacting factors influenced their dimension during the design process to find a formula covering all occurrences.

The spreadsheets helped as well to figure out the overall weight and display the center of gravity to avoid a tilting of the construction when suspended from the exhibitions spaces ceiling.

6.3. Joints - Logistics and Assembly

A high degree of planning and prefabrication enabled an easy assembly process. A key factor for this endeavor was the avoiding of on construction site measuring and adjustment. Therefore self registering and load bearing connectors were necessary. Research reports and papers show that friction based joints serve well for this purpose (Kilian 2003, Schindler 2007). Besides this we used tenon joints with wood pegs, which are as well self registering. Solely the junctions between beams and rails were not self registering as they were carried out as double cuts or notches. Machined marks served here as guidance for assembly

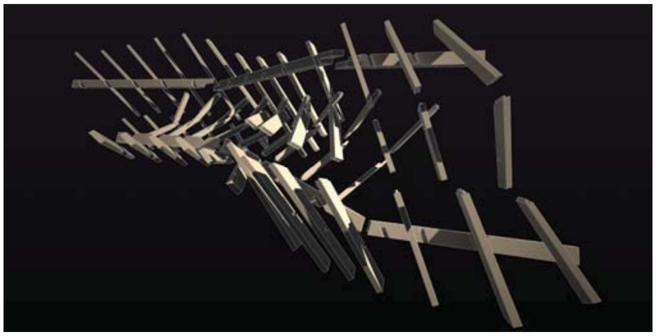

Fig. 8: exploded view of the members with integrated joints and cuts

The fabrication of the 65 individual wood beams on the wood joinery machine took 3 hours. The assembly with 4 students took 4 hours. Within the dry wood the joints fit generally well.

Especially the introduction of the diagonal beams, had a positive effect, as they created three geometrical registration points for the geometry –a structural self centering system.

7 Conclusion

The research projects output can be examined on the field of design and the field of production.

The crucial part for the seamless process from design to production was a clearly defined logical structure. Strong alterations within or the introduction of new logics and topological change proved possible however time consuming.

The process of materialization was the most time consuming part in the process. The amount of work to adopt the model especially to maintain geometrical flexibility in a new generation where sever. However, once the production parameters had been implemented within the system, geometrical changes could be conducted easily in design giving freedom to explore intensively. In a total the component based parametric model proved to be flexible and expandable.

Interactivity was the key to the design process design. The instant change of the model due to user inputs enabled a fluid process.

In terms of production the high amount of planning, the precision of the fabrication, the self registering system and the logical system that formed the basis of the structure enabled a fast assembly process. The chosen wood connections could adapt to geometrical extremes and provided good structural strength.

8 Further research

Further research is necessary in structural strength, actual costs and assembly within the chosen approach and how similar system can be embedded into architectural practice. This includes the facilitation of digital fabrication and material knowledge in the design process. The further integration and feedback of parameters of material, tectonic and derived properties (i.e. lighting and other performative data and the combinatory effects of compound materials and elements) through integrated simulations into the design, gives design a higher accuracy while opening space for free exploration. A further feedback of the design tools, i.e. with an integrated proposal of design solutions seems worth to be discussed when a customized tool reaches a mature general level.

Besides this the project is pointing at the changes in the profession (Kolarevic 2003), wherein architects become toolmakers. Customized tools help to materialize complex designs and enable a new design practice. This practice might find better ways of communicating to clients and environment as it is based on the negotiation of rules and parameters rather than images.

Acknowledgements

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Poster Abstracts

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Breider, Janwillem and Coenders, Jeroen (TU Delft / Arup, The Netherlands)

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Using Parametric Software to Expand Geometric Limits of Vernacular Materials

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Abstract

Our assumptions about the world of technology and design are leading us astray. We are being pulled unequivocally towards notions of efficiency (time and cost) and towards the idea that we are buying ourselves back into the business of design development. In reality we are not repossessing anything, but are simply passing our cost and time savings on to our consultants, contractors and clients. Parametric design, BIM (Building Information Modeling) and digital fabrication methods are rendering us, as architects, further obsolete and creating a world in which we are even more likely to create another big box store or a second lot of condos, with only the requisite shift in material or articulation. We propose to demonstrate that an alternative method could be deployed using the complex capabilities of this software to further the form and compositional possibilities of vernacular materials.

Keywords: Applied parametric software, CATIA, material

1 Introduction

We need only reference the introduction of Computer-Aided Design in the early 1980's, which promised a time of change in the field of design, to see that the speed and precision of technology is truly seductive. CAD technology was billed as device for making firms more efficient, thus reducing the amount of time spent on each project and netting the firm larger profits. This initial venture into CAD left some of the professions elder statesmen clamoring against these advancements. This resistance argued that digital software reduced design development in favor of a higher level of productivity and efficiency; as we all know the efficiency provided by CAD software has overwhelmingly won out and has now evolved into BIM. BIM software has enabled "smart models" to be utilized from early in the design process, streamlining the transition between design, documents, and construction. These smart models allow for precise material definition and custom detailing to be represented in three dimensions while producing automated versions of "traditional" construction documents, all from one three-dimensional architectural model. This time the profession, both young and old has wholeheartedly accepted the transition to information modeling under the auspices of an even more efficient model of practice. Though the reality of offering copy and paste building components once again reveals our inability to dissect the material or programmatic shifts necessary for creating a heterogeneous urban environment.

Another offshoot of the software development which was empowered by IBM's FORTRAN language, along with other CAD software, in the late 1970's, was geared towards the more lucrative aerospace and naval engineering fields, including, CATIA, Pro/Engineer and CADAM.[1] CATIA, originally developed by Lockheed and then sold and repackaged for a larger audience by Dassault Systems, was created as a platform for aeronautic design. CATIA by definition was designed to create monocoque design forms with diaphragm structural constraints provided by two rigid skins, one interior and one exterior. It was also capable of modeling highly complex forms driven by the aerodynamics of the object. It's reliance on NURBS based geometry allows the software to describe these shapes in an efficient and precise manner. This type of articulation has been incredibly important in the advancement of computer-aided design, as it empowered a new aesthetic into the design lexicon.

2 Parametrics

Not only did CATIA fully capitalize on the geometric capabilities of NURBS curves, but it also allowed for parametric connections to be made between those geometries and other constraints, both geometric and algebraic. The integration of parametric software into the design and construction process allows for multiple construction details/techniques and designs to be pursued quickly and simultaneously once a defined set of parameters connected to a geometrical set have been defined. These parameters enable the software to reject a possible design whenever any criteria are not matched. The power of parametric design software is paramount when dealing with the interdependent systems and advanced compositional characteristics of alternative geometries now being utilized by architects and engineers.

Parametric software's capabilities mimic the controls of other three-dimensional software, except that it incorporates associative geometry through a set of constraints. These constraints allow for articulated structural geometries to be parametrically linked to a control geometry(ies). These parameters allow the entire model (structure and skin) to be controlled by definable objects or curves, including regulating geometry, a Boolean variable or a mathematical equation. This method provides for a high level of geometric control that can easily be modified even very late in the process. As well, this software allows customized details to become a variant of a base detail, essentially utilizing the software to allow a set of mass customized details to permeate the system.[2]

These customized details can be anything, they are defined only by their geometric form. As with most every three-dimensional modeler, CATIA comes preloaded with its own set of default connection methods. As CATIA was initially formulated for use in the aerospace and nautical engineering industries, it is naturally equipped with joinery more typically associated with these fields. These tend to be joints for connecting steel and aluminum in typical methods, however they can be deployed in very unconventional ways. While bolted and welded connections are relatively ubiquitous in architectural design, this type of convoluted joinery is very suggestive of specific construction techniques outside of the architecture industry.

3 Reconception of The Tool

We propose to reconceive the way in which we use the capabilities of this software. Having considered the process of design utilized by the Skunk Works[3] in the 1970's to design the F-117A stealth fighter, and previously the SR-71 spy plane. Skunk Works in the development of the crystalline form of the F-117a fighter first calculated how to create the minimal radar signature of their aircraft, a parameter that had to be absolutely perfect. By defining one specific parameter they were ensured of a successful design per at least one definition. Once this primary task is successfully developed, they worked to solve all of the other limitations articulated by the primary parameter, the geometry. This required a fly by wire system, an on board computer which constantly monitors the aircrafts, speed and orientation and makes instantaneous minute adjustments to keep it steady. We propose using *Digital Project* with the same method of prioritization. We must begin by defining the formal limitations of the material or construction method we intend to use.

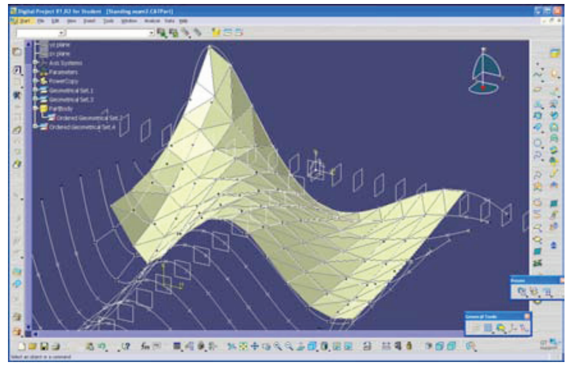

Figure 1- Gehry Technologies Digital Project (CATIA) model of Standing seam metal roofing bent (broken) to form an unconventional skin.

The use of CATIA, or other parametric design software, could just as simply use a bow/banana truss or a space frame as construction methods, if only the form were linked back to the definition of these components. We propose that in fact this is a far more ethical and constrained method for deploying the software. We begin by defining and analyzing a system that we would like to explore. One of the first methods we attempted to use was conventional metal roofing, manufactured throughout the world and deployed in a myriad of types, environments and programs. Firstly, we have modeled a tessellated use of typical 5-V metal roofing, maintaining the typical interlocked connection along seams and through a bracket back to a structural system.

Figure 2- 5V Metal Roofing test

To test this hypothesis we modeled up the skin with 5V metal roofing a material very typical throughout rural America. This material made for an excellent test as we were able to quickly trace our unrolled surfaces onto them and break them into tessellated forms. Though their real flexibility lie in its ability to be connected anywhere along its seam through the piece next to it and into the structural system underneath.

This model functions within certain limitations that were derived from the software. In fact, the system in reality is far more constrained than we might have imagined. Each time a component or triangular shape panel takes on a steeper or more shallow angle it can have a direct effect on the piece immediately connected to it, and dramatic effects on components further down the line. We have also realized that this model does not function with the typical lofted surface. The geometry is linked such that to have two curves defining a surface does not allow for the relational movement the system calls for.

The alternative to using a predefined surface is to use the constraint systems built into the software to constrain distinct points to one another. Each constraint whether coincident, or planar, allow for distinct types of movement at each point in the system. Then the user can use this predefined "flat" model to articulate patterns and see immediately the effects that moving one point will have upon the rest of the system. As well, you can find moves that one may ask the system to do that the system simply cannot accomplish. The larger the system gets the more panels the more constrained the system becomes and the closer to completely flat the system wants to be.

Figure 3- 5V Metal Roofing test

We imagine that this same system could function far more cleanly with a typical run of standing seam metal roofing. With standing seam metal roofing we will have to connect using brackets and very specifically locate the points of connection prior to construction. The system we proposed will cut the seam along each edge at particular intervals defined by the system. This geometrically defined and constrained system limits the form, by connecting the moves which are made along one edge of a surface by pulling or pushing on the opposing edge, to increase the area of the shape near the altered edge.

Figure 4- Standing seam test on frame

Though the method doesn't accommodate specific forms that a designer may envision, it gives the designer a form driven by its materiality, in a smarter method similar to that of algorithmically defined form-making, so popular in academic circles. This method can make for a much more culturally coherent and connected design method, one which expresses efficiency and takes advantage of digital fabrication methods not as a method for making elitist icons, but for making inexpensive poignant designs.

4 Conclusions

The tools embedded in the parametric technology such as CATIA create a system for the use of large sheet metal goods to be cut down inefficiently and applied to skeletons of disjointed and grotesque usages of steel and structure. These same tools can be reverse engineered to create systems using inexpensive and conventional cuts of materials to create objects that are identifiable and unique while remaining within the constraints of typical construction processes. In contrast, by creating methods for deploying conventional materials and methods in unconventional we ways we can educate the profession to create buildings of craft and precision, icon and expression, for clients that can really use them for the betterment of their business or cause. Though parametric software has become synonymous with excess and flippant design, the software also comes with the ability to utilize materials in unconventional and affordable ways. Technology, perhaps for the first time, is capable of understanding a material's constraints; we must choose how to employ these tools or risk that our profession will become further removed from the definition of our environment.

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StructuralComponents, parametric associative conceptual structural design tools

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Abstract

The author has developed a set of design tools for the conceptual structural design of high-rise buildings. These tools have been developed on top of the GenerativeComponents [Aish, 2005] platform by Bentley Systems. The method allows the structural engineer to conceive a parametric associative model, and perform analysis in real time. The set of tools are based on a Lego block approach, together with a dash board view approach for the output, which combines composing a conceptual design from large building blocks for easy and quick modelling and real-time, on-the-fly analysis for fast tweaking of the relevant parameters.

This method is relevant for the stages before an architectural and structural geometry is created and on which this geometry can be based. In this stage a conceptual design is created of the architectural shape and structural system. The results from this method can be developed into a geometrical description of the concept with the structural parameters, properties and their derivatives as a starting-point, to inform geometrical design by conceptual design.

Keywords: conceptual structural design, high-rise, parametric associative design, structural design tools, computation

1 Introduction

Through history the role of the classic master builder has disappeared. By expansion of the knowledge on architecture and construction this role has been taken over by specialists that focus on seperate disciplines. The intelligence of a structure is no longer part of one person's knowledge. This specialisation means that architects and engineers can focus more on their tasks. However, the spreading of the knowledge over multiple parties slows the design process down. Since a design process has a strong cyclic character, they will have to communicate regularly to steer the entire process in the right direction. Poor coordination can result in a slow and inefficient design process.

In the current design practice more and more use is being made of Computer Aided Design (CAD), by both architects and structural engineers. This offers the possibility to create free-form designs with more efficient bearing structures. Both architect and structural engineers make use of design tools, adapted for the specific task that is required. However, the specialisation of both disciplines has resulted in a poor compatibility between these tools. Exchanging information between the design tools requires a relative large amount of time, delaying the design process. More so, the various parties cannot work on the same design simultaneously.

2 Objective

The background above illustrates that a gap has emerged between the architectural and structural design process, especially concerning the CAD methods being used by both. This thesis aspires to bridge the gap between both disciplines, from a structural design point of view. The objective is to develop structural design tools [Coenders & Wagemans, 2005] with which the structural engineer and the architect can generate a preliminary design in a short time span, that can be used for further design. Decisions that are made in the beginning of the design process are of great influence to the later design stages. Therefore it is of great importance that a sound and efficient structural system or concept is developed in the start of the process.

The design tools are based on two basic principles:

- Lego block approach. The model can be constructed by a set of pre-programmed components that allow the user to model the structure and perform structural analysis quickly and easily.
- Dashboard view. In order for the tools to be easy and quick to use, the output should be interpretable in a single glance of the eye, like the dashboard of a car.

Figure 1: the Lego block approach and the dashboard approach

3 Categorisation

At the base of the large scale components a categorization of modern structural systems in high-rise buildings has been used based on various literature sources [Taranath 1988, Smith and Coull 1991], amonst others outrigger bracing, tubular structures and mega-structures.

4 Software

These structural design tools have been developed on top of the GenerativeComponents (GC) [Aish, 2005] platform. GC is a parametric associative design system with predefined geometrical objects (called features), capturing the logic behind the design in parameters and relations which can be created and controlled by the user. GC uses the concept of features (components) to build models. Trivial examples are geometric entities such as points, lines and surfaces etc. GC is mainly used in the field of architecture and offers possibilities towards rapid prototyping and digital fabrication.

The concept of the GC platform provides opportunities for the development of structural design tools that are fast and flexible. However, GC has little structural analysis capabilities embedded. New features will have to be added, and a proper analysis method will have to be implemented that supports the parametric associative design concept.

In the future development of GenerativeComponents and this toolset more multi-disciplinary features can be incorporated

5 Analysis

The analysis method has to comply with some conditions:

- Flexibility – when the structural components or the structural system that are part of the design need to be adapted, these changes should be able to be analysed without having to use another analysis method.
- Speed – because the architect and structural engineer want to work side-by-side quick results are preferred.

In the first attempted approach closed form expressions have been derived to be used to describe a structure's behaviour as rules-of-thumb. After initial investigation it proved that this approach was not suitable, because closed form expressions are very case specific, there is no general method that can be used for every structural system. More so, the complexity of the expressions increases when the structural complexity increases and which makes the system unusable.

The chosen method is a combination of the finite element method and classical mechanics [Steenbergen, 2007]. The basis is a small finite element model where the elements represent large-scale structural components (stability shafts, outriggers, frames). This results in a system with a limited amount of elements and a limited amount of degrees of freedom, which benefits the calculation time. Different from conventional finite element methods classical mechanics is used to determine the total system behaviour rather than shape functions. This offers exact analytical results and is able to provide quantitative and qualitative results. The elements represent the major structural elements of a high-rise building, like cores, outriggers, columns.

The various analysis steps are:

- Determination of element stiffnesses, boundary conditions.
- Coupling the different elements and assembly of the global stiffness matrix.
- Determine local and global load vectors.
- Solving the system and obtaining the nodal deformations and forces.
- Determination of total system behaviour by the use of differential equations, using the nodal results as boundary conditions.

The steps in the analysis are split up and translated to new features in GC, which from now on are named StructuralComponents.

The StructuralComponents can work from a geometry deriving the stiffnesses or can work towards architectural and structural geometry by user-defined stiffnesses.

6 StructuralComponents

The new features that are created in GC are called StructuralComponents. These components can be used to compose a conceptual design and perform on-the-fly analysis. The various types of StructuralComponents will each perform a part of the analysis, together with other tasks that are necessary in the structural design process. By linking various StructuralComponents a structural design can be generated.

The types of StructuralComponents are:

- StructuralModelComponents (SMC)
- MechanicalAssemblyComponents (MAC)
- LoadModelComponents (LMC)
- AnalysisComponents (AC)
- ResultsProcessingComponents (RPC)

Figure 2: example of possible structural configurations

The StructuralModelComponents (SMC) represent the elements within the finite element model. For each relevant type of structure an SMC can be developed, for which the behaviour will be described by the use of differential equations. With the various types of SMC's many structural systems can be modelled. The SMC determines the mechanical properties of the structural element, resulting in a local stiffness matrix. In the current implementation SMG's are present to model bending action of a core and outrigger system.

The MechanicalAssemblyComponents (MAC) assemble the global stiffness matrix using the local stiffness matrices from the SMC's. The MAC's first apply "node" numbering to all SMC's. Subsequently, it uses these assigned numbers to assemble the entries from the local stiffness matrices in the proper position in the global stiffness matrix. The boundary conditions are assembled similarly.

The LoadModelComponents (LMC) model the loads. A uniform distributed load, both lateral and vertical, is translated to equivalent node forces for each SMC. The local load vectors are assembled in a global load vector. In high-rise the lateral loads are usually governing, and in some regions seismic loads may be relevant. Furthermore the vertical load may increase the forces and deflections due to the deflections cause by the lateral loads. This is known as the P - Δ effect. A good estimate of the wind loads is hard to produce, and has not been part of this research project.

The AnalysisComponent (AC) solves the global system using an LDU-decomposition algorithm. The global boundary conditions are eliminated from the system, and the results are given in nodal deflections and forces.

The ResultProcessingComponents (RPC) use the results from the AC to determine the total system behaviour, continuously over the height of the structure. The RPC's can present the output in the form of diagrams and dials. The presented data provide the engineer with qualitative and quantitative information about the structure's behaviour.

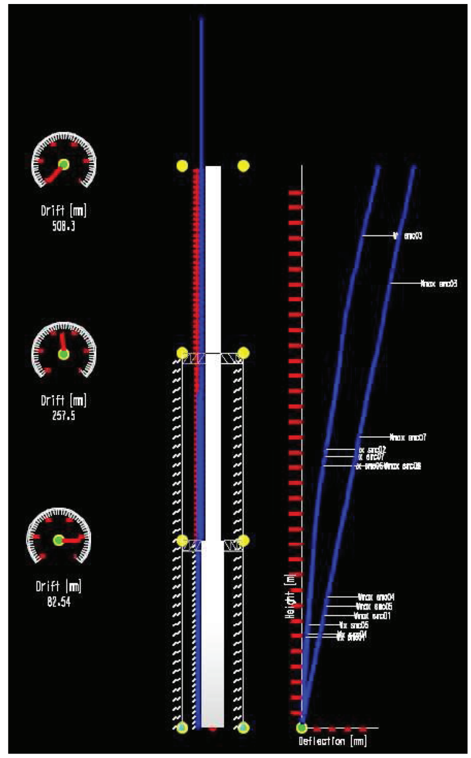

Figure 3: output in diagrams and dials

7 Application

The StructuralComponents can be used by the user like "Lego" blocks to model a structure. The StructuralComponents provide real-time results. The tools can be used to compare a variety of structural systems quickly, even in one view. One can also compare results for multiple load cases real-time in one single view, by creating multiple LMC's, AC's and RPC's. The user can use diagrams to assess the qualitative overall structural behavior, but can also monitor specific values at locations determined by the user, by using dials. The components can be created with either geometry of stiffnesses as input. The output consists of deformations, force distributions, strain energy diagrams and magnification factors.

The chosen approach provides a very versatile method which is suitable for conceptual structural design. The many possibilities that can be used allow the user to use StructuralComponents for various design purposes. The structural engineer can easily influence the behavior of the designed structure by tweaking the parameters with which the design and the components are defined.

8 Discussion

In the structural design process many computational design methods are available. However, a quick and easy method that allows the structural engineer to create a conceptual design whilst sitting next to an architect is not yet available. In current day practice an engineer either uses rules of thumb, simple mechanics, or otherwise starts to use finite element methods. The first option cannot yield more than a very gross estimate, and mechanics are very case specific. Finite element methods are versatile, but also laborious, and therefore unsuitable for conceptual design.

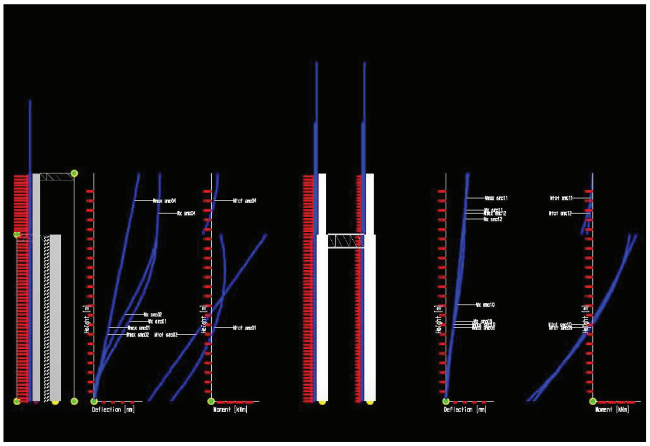

Figure 4: multiple structural alternatives in one view

The current state of the tools allow the structural engineer to design structures consisting of core elements, columns and outriggers. The user can evaluate designs very easy and quick, so he can provide feedback to the architect immediately.

The development of these tools show that the parametric associative design approach is very suitable for conceptual structural design. Further development may lead to a more extensive toolbox that can be used in this method.

9 Conclusions

- The developed set of structural design tools provide a quick and easy way to model bearing structures for high-rise buildings, and make an accurate estimate of the structures behaviour.
- Parametric associative design methods are very suitable to be adopted in conceptual structural design.
- Simple validation has shown that the method is accurate compared to finite element method with errors in the order of magnitude of 0 to 5%.
- The real-time analysis allows the structural engineer to sit next to an architect and provide immediate feedback.
- The hybrid analysis approach has a lot of advantages over a classical mechanics approach. The method is versatile and can be applied to every structural system.

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Catastrophes in architectural model space

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Abstract

Many contemporary architectural models replace explicit single instance geometry by geometry defined by explicit variables. They move architectural conception from Platonic idealism to morphogeneticism and, in doing so, promise smooth transformative spatial qualities. This short paper explores, through example, the extent to which architectural models are sufficiently homogeneous in their geometrical representation to fulfill this smoothness of space and what the singularities and discontinuities mean for the architectural design process.

Keywords: architecture, algebra, singularity, catastrophe, mathematical function surfaces

1 Introduction

In architecture, it is impossible to cleanly separate means of conception and means of representation. Models are simultaneously a mode of engaged thought and a means to communicate intent. However there is a distinction between a static geometric model that represents a single iteration, a frozen or even 'final' moment in the design process and a responsive model that can be changed formally or qualitatively in answer to new input information, changed or refined intent, streaming data, or simply the adjustment of the relative influence of each of many design drivers.

These are often paradoxically analogic engagements carried out at high level on a digital discrete system in the tradition of the great physical and material form finding analogical models: consider the tensile models of Frei Otto, cloth and ice models of Heinz Isler and their progenitor, the hanging model of Antoni Gaudí. These analog models supply through the interaction of physical behaviours and material constraints, measurable formal geometry responding to particular support and loading conditions. The variables are potentially numerous but typologically limited. They generally operate within a limited range of change and vary smoothly within this range.

The virtual models or systems, by comparison, take, as their medium, geometry itself and have only this means to construct material constraints, physical behaviours. Not only are the numbers of variables and relations unlimited but the geometries and relations within a single model can be very hybrid. What does this mean for digital form finding? I will try to shed some light on the question with three distinct examples from design projects.

2 Simple algebraic engagement

Simple algebra is a useful adjunct in design modeling, for instance, for saying something about serial relationships very concisely. An example of this is the growth algorithm for the steps in the model of the crowning element of the portal to the west transept of the Sagrada Família church in Barcelona [Burry and Burry 2006]. By comparison with most of the formal surface geometry in the church, this element appears geometrically simple; it is a rising multi-tier staircase of rectilinear blocks sitting like a pediment above a colonnade of much more organic appearance and a frieze of cupped hexagonal prisms.

By making reference to the only solid piece of historical evidence for the geometry, a surviving photograph of the drawing of the elevation of the façade made in 1917 at the time Gaudí completed the last proposal for this elevation, it appeared that the position and distribution of the steps in this ascending stepping giant's causeway was not closely related to the changing intercolumniation below nor to the distribution of the hexagonal figures in the frieze. This greatly simplified the interface between this element and the rest of the assembly in the relational model. A simple constraint system could be set up to fit the element to the lower and upper limits of its 'site' in the model, maintain the linear pitch lines through the staircase, ensure the vertical coincidence in the height of certain repeating patterns of steps through the assembly and marry this with the curved profiles of the steps in plan.

Figure 1: part of the 1917 photograph of the drawing of the Passion façade indicating the stepping 'crestaria' crowning the portal and upper colonnade of the west transept

Two big questions remained. From the photograph it was difficult to discern definitively how many of the repeating stepping units occurred from base to top, and, closely related to this question, the dimensions of the steps in width, depth and height increased from the base to the top in a way that was clearly not linear. Measurements from a high resolution scan of the photograph of the step heights and depths were each plotted against a step number (n) from 1 to N. (The x and y coordinate values for the edges of each step in the photograph, by comparison, would of course give the linear result of the pitch line.) Curve fitting software gave a good fit for a quadratic equation. The principle aim in the context of the project was to arrive at a three dimensional form that fitted well the form shown in the photograph of the Gaudí drawing. The short term tactic in the design process was to slot a working growth algorithm into the digital model that satisfied the overall constraint criteria, could be tweaked to adjust the distribution of the steps for a better fit and importantly could be replaced, like a modular component, if new evidence pointed to a different function type or a less geometrically regular pattern. The result was a very flexible configuration that met all the eternal constraints but could change its rate of growth or the overall number of steps within viable geometric limits.

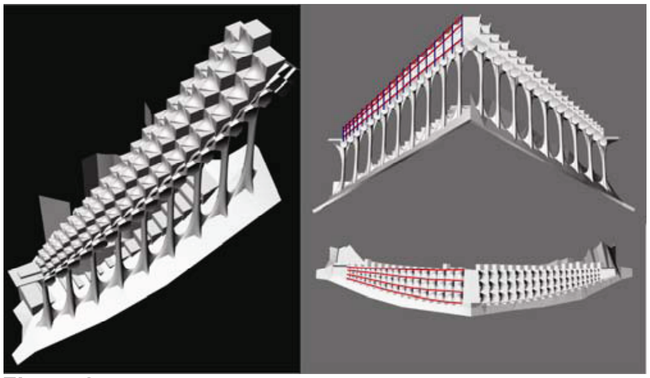

Figure 2: The model of the stepping crest showing the changing steps that are subject to a variable growth function, adjusting the number and distribution of steps and the elevation showing linear pitch lines and plan showing curved profiles.

2.1. The algebra

$ln = a+bn+cn^2$

- Where ln is the distance of the front of each step in the direction of their parallel risers from a starting point,
- n is an integer from 1 to N assigned to each consecutive step,
- LN (the total length of all the steps combined in the same direction) = $a + bN + cN^2$ = (a constant or more accurately, an external parameter),
- a = 0.1 (through empirical trial – it controls the starting point),
- c = (L-a/N-b) * N
- N, the total number of steps and
- b is the "growth hormone"
- both the last two variables could be controlled in a spreadsheet.

The form of the steps could vary smoothly within a fairly limited range of the variable b for any given value of N to yield geometries that were viable within all the other constraints of the system.

Other functions were also trialled by way of comparison, for instance sine and cosine to see the effects.

3 Curious bifurcation

This second example is also taken from constructing the same extensive relational model for use to reverse engineer Gaudí's as yet unbuilt design proposal for the upper part of the western of the Passion façade of the Sagrada Família church. A major element of this assembly is a colonnade of slightly gaunt bone-like columns. Mark Burry had already developed the geometry for these intertwined columns. It was a combination of an elliptic hyperboloid of one sheet for the central trunk of the column combined with eight paraboloid branches married along the straight lines common to these two different types of ruled surface. Similarly each column bonds with its immediate neighbouring columns through shared rule lines on the lapping paraboloid branches. This was developed in response to a detailed understanding of the geometric codex that Gaudí developed for the design for the sculptural surfaces of the church as well as direct reference to the photograph.

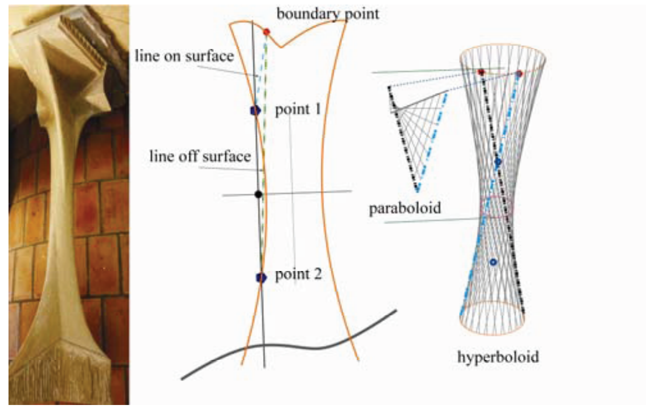

Figure 3: Soft stone prototype at 1:5 scale of one of the columns to show the geometry of the intersecting hyperboloid and paraboloids. There are two possible points of intersection on the surface for the lines of intersection between the hyperboloid and paraboloid, only one of which is 'correct' for each combination of variables controlling the surface shape.

The difficult part of assembling this form: locating the straight lines on these surfaces and their key intersections had already been solved and coded in a Com function in collaboration with Peter Wood, Wellington based engineer and programmer. This function could be called within the parametric model. The specific inputs from the context model determined the unique shape and orientation of each individual column in context.

As the main model grew and developed, it was central to the collaborative process of moving towards consensus and design resolution. The form of the assembly continually morphed through repeated variation of many of the parameter values. Almost inevitably, in this process, some of the column geometry would fail. Closer inspection revealed that some of the junction lines between the hyperboloids and paraboloids no longer lay on the hyperboloid surface. The script to locate the point and lines was running on cue, the reaction in the main program was working. Yet the problem persisted.

Over this period, parts of the model structure were also redeveloped, including rebuilding the columns from first principles using geometrical tools in the main program. The geometric sequence of this process produced two points on the hyperboloid surface, one of which lay on two straight lines on the surface passing through two chosen points on the surface boundary. The second point could be disregarded; or could it?

"Never assume", a familiar aphorism from architectural professional practice lectures many years earlier now came to mind. By carefully observing what was happening as other parameters in the model were changed, through their impact, changing the shape and proportions of the columns, it became evident that it was not always the same one of the two points on the particular column that generated lines lying on the doubly curved surface. This was the slow beginning of a realization about the wider geometrical context.

To try and define the conditions when each one of the two points should be selected, I first listed all the parameters, a change to the value of which, would change the column. Without trying too hard or moving too far from the immediate vicinity of the column, I listed forty-six of these. It was at this point that understanding started to dawn. This was essentially a forty-six dimensional space. It was also not a smooth continuous space but a space with discontinuities and singularities and, in this case, a classic catastrophe. As parameters were changed to subtly alter the shape and inclination of the leaning columns, the points that created the intersection creases between trunk and branch would slide smoothly across the hyperboloid surface until a critical point was reached, at which time, this intersection point would abruptly jump to a completely different point on the surface.

This simple geometrical model constructed through the synthesis of Euclidean and conic elements had become, through the dependencies created between the geometrical objects in the space a complex space in which Thom's mathematical theory for biological systems could be experienced first hand [Thom 1975].

4 Smooth periodic space

This third example looks to a more holistic approach to representing space algebraically.

It is taken from an undergraduate student project. The context was an experimental research class bringing together architecture and civil engineering students to find ways to collaborate on design. The aim was to avoid the dual traps of structural pre rationalization (here's a fine structural system – can you design using it?) and structural post rationalization (please make this design stand up now?). Could they negotiate a third way, 'co-rationalization' where the architectural design and structural consideration were concurrent in the design process? The semester long course was divided into three parts. In the first part architect-engineer partnerships explored technique, in the second, they applied the techniques they had developed in design projects, in the third part they were to start over and design for a challenging site.

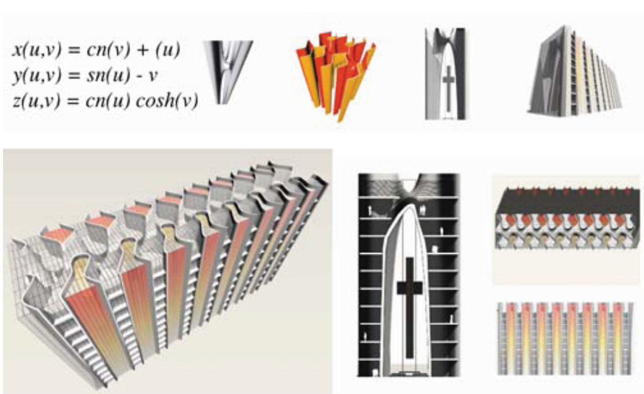

Figure 4: The Hybrid Cathedral with a surface from a gamma function mediating between congregational space and

This description hones in on one particular partnership as they moved from the second into the third stage. This partnership had worked together in the second stage and developed three conceptual design projects exploiting a common interest that they had identified: mathematics. This manifest through assembling a library of mathematical surfaces: surface models of regions of various mathematical surfaces and the functions of which each represented an instance. Selected surfaces had been used to generate design proposals: a railway station roof, a tower block and a hybrid urban cathedral with high density housing wrapped around the monumental space, the undulating surface of a gamma function mediating between the two programs. At this stage, they modified the surfaces from their surface library through small changes to the coefficients in the function and through cutting the surface in different ways, resulting largely in differential scaling and making openings.

For the third stage they chose as their site, the mouth of a Corio bay off Port Philip Harbour that had once been proposed for the site of a freeway bypass. They proposed an inhabited bridge in the tradition of the Rialto, Ponte Vecchio or Old London Bridge. In this case they speculated that the private public partnership would mean that the small scale private housing on the bridge would contribute to funding the huge causeway, bridging over a shipping canal at its midpoint.

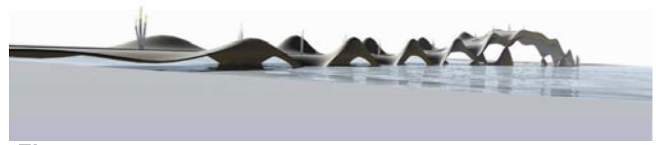

Figure 5: Bridge based on a Jacobi Elliptic function (image by Steven Swain)

Their own brief for this project provided a short list of very clear critical parameters: constraints on the gradient and curvature of the freeway over the top of the bridge, structural bays between piers supporting the bridge, the great height and span of the bridge over the shipping canal. There were also more qualitative drivers: achieving height, shape and curvature in the undulations of the surface between structural piers suitable to accommodate the waterside housing on the bridge.

It was quickly clear that their cursory engagement with the mathematical functions generating the surfaces in the second stage would not be sufficient to create a surface that would meet all the criteria for the bridge. This excited a period of experimentation in which they started to understand the function better through more direct engagement, superposing new functions that provided detailed surface articulation, allowed control of differential spacing between the structural piers, appropriate curvature of the bridge in plan to meet the springing points set up by the approach roads on either side of the bay.

At a certain point in this goal oriented exploration, they were frustrated, however to find themselves unable to arch the surface appropriately for the bridge to make it's crossing. At this point they turned to experts, the mathematics department and Paul Bourke, an astrophysicist then at Swinburne University, now at University of Western Australia. Paul was able to solve this for them and simultaneously parametricise their function so they could directly control the shape in response to the parameters they had established for the bridge.

$$x(u,v) = ff(\sin(v\,ee)) + cc(u)$$
$$y(u,v) = dd(v)$$
$$z(u,v) = cn(aa(v))\cosh(bb(u))\,0.1\left(cn\left(\frac{u}{2}\right)\right) hh\left(\sin\left(\frac{v}{gg}\right)\right) + ii\,e^{\left(-\frac{0.5\,v\,v}{jj\,jj}\right)}$$

Figure 6: the function parametricised with parameter 'aa' controlling the number of piers, 'bb', their height, 'cc' the width of the road, 'dd' the length of the road, 'ee' cycles in the xy plane etc. (image by Steven Swain)

Now they had an undulating shell structure, highly organic and variable in its form, several kilometres long. It could morph in response to a specific set of drivers and be transmitted between design participants in three short lines of function. It was this notational economy that ultimately delighted the protagonists and made them feel that they were somewhere on the track to revealing the secrets of a shared or co-rational design process.

Figure 7: Image of the inhabited bridge from the water (image by Steven Swain)

5 Discussion

The first example above describes the use of algebra to make a very specific component of a larger model. This model was built to reverse engineer some specific static geometry by trying to discern the underlying pattern, the pattern that connects [Bateson 1979]. We aimed to achieve authenticity while interpreting the intentions of Gaudí, probably using approaches that were different to his. There was no requirement for the stepping assembly be infinitely morph-able, simply to be able to concertina gently within a given but still variable space to achieve a better correspondence with a historical photograph. Moving outside the viable range for the key variables would soon 'break' the geometry. This is because the other components of the geometry were created synthetically by intersecting planes and curves and applying surfaces to the results. It takes little to create non viable intersections or steps following curves in plan that step out from a neighbour where previously they stepped in. So while the form varies smoothly within this small region of the design space, it, nevertheless, has complex boundaries and discontinuities through its hybrid nature.

The second example was perhaps the most surprising. While building up a variable design model from Euclidean elements and conics (Euclid is also credited with writing a lost work on conics) their cumulative effect when related within a single system is to exhibit behaviour attributable to "bad smooth functions", mathematical behaviour defined only in the twentieth century [Casti 1996].

The difference between the third example and the previous two is clear. The principle spatial device in this proposal was a continuous periodic surface (albeit it based on a Jacobi Elliptic function which is doubly periodic and meromorphic). The space is thus defined by a mathematical function, rather than resulting in one by hybrid means. Mathematically at least, it is a more homogeneous space. Nevertheless, the form is not only driven by parameters given by the design of the bridge but highly varied and surprisingly animalistic in its local manifestation. This is a space that can be controlled top–down through editing a function to meet the local formal and performance criteria. There will be no discontinuities or surprising catastrophe type events unless hybrid geometries are built onto this homogeneous scaffold. In this case even when needing to add the internal service road and the lanes on the freeway in order to be able to create renders of the bridge with indications of scale and use, it was found more successful to add these using the function than to try and add them externally in a modelling program.

Conclusion

Relational models are systems that may result in geometry and geometrical behaviour beyond, or meta to the geometry used to construct them. There are many ways to approach this meta design of the system. This paper illustrates and contrasts three, giving reasons behind the different approaches and highlighting the constraint and behavioural differences between them.

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Sloping façade building section: an exploratory study with shape grammar

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Abstract

This undergoing research proposes the categorization of buildings based on morphologic criteria. A group buildings which have sloping façades as a common characteristic was defined. Next, a shape grammar was developed, with the objective of establishing a set of rules that could be used to confirm if other designs belong to the same family of objects, and to which extent.

Keywords: shape grammar, sloping façade

1 Introduction

The present research proposes an intersection between the study of precedents in architectural design and the formalism known as shape grammars (Stiny and Gips, 1972). This idea is not new. Eilouti and Al-Jokhadar (2007), for example, have proposed the use of shape grammars to structure the "unstructured information embedded in precedent designs" (p.34) that are present in Mamluk architecture.

Shape grammars have been used for identifying architectural styles focused on common factors such as a specific designer, style or time and geographical range. Examples of the use of the shape grammar formalism in these cases can be found in Mitchell and Stiny´s (1978) Palladian grammar, Flemming´s (1987) grammar of Queen-Anne houses, and Çolakoglu´s (2003) study of traditional Bosnian houses, respectively.

In the present study we propose to focus on a different aspect –a particular building element - as the starting point for the definition of a shape grammar. Besides, instead of a specific style, the concept of family resemblance, as defined by Wittgenstein (1953), will be used, in order to identify the use of precedents in design. According to the German philosopher, there is nothing that is common to all members of a family, although they may be characterized by certain similarities and relations with each other. In other words, a shape grammar developed for characterizing a family should be less deterministic than a grammar developed for explaining a specific corpus of designs.

2 Computer implementations

Referring to the purposes of computer implementations of shape grammars, Gips (1999) suggests four reasons for the use of grammars:

Synthesis - generating shapes based on a shape grammar ("the most common task");

Analysis - determining if a given shape can be generated by a given grammar and, if so, determining the sequence of rules that must be used;

Inference – defining a shape grammar that can generate a given set of shapes;

Generative design - defining grammars as a process of designing; an approach based on Knight's (1998) statement that "the process of developing an original grammar is analogous to the traditional design process".

This research starts as an **inference** exercise, in which a shape grammar is inferred from a selected corpus of sloping façade buildings. It proceeds with an **analytical** and a **synthetic** studies, in which other existing buildings are tested to see if they can be generated by the rules, and new designs are generated by the grammar. Finally, the study proposes the use of the grammar developed as a starting point for the development of new **generative design** rules, for example by transforming the original rules, in order to generate novel designs.

3 Sloping façade

The common building element in the corpus of designs analyzed in this study is the sloping façade. Buildings with sloping façades have been present since the construction of the ancient pyramids in Egypt. The present study, however, will focus on the XXth century. Starting with several cases found in Brazilian modern architecture, it also looks at possible precedents in European and American architecture, with the objective of establishing a set of rules that can be used to confirm if a given design belongs to the family, and to which extent.

Reasons for the use of sloping planes in architecture may be functional (as the basis for stairs, ramps and bleachers), structural (such as those proposed by Nervi, 1956), or related to visual perception (as suggested by Arnhein, 1975) and climate control. These reasons are taken into account in the present study.

Figure 1. Paulistano Atletic Club – Paulo Mendes da Rocha – 1958

The sloping façade buildings identified so far can be grouped in two major types, according to their section: those with actual sloping planes, and those in which the sloping plane is just suggested by structural elements. Some of the buildings combine both sloping planes and structural elements, thus characterizing a hybrid type. Another possible classification of the buildings is related to their volume, which can be generated by two different geometric transformations: translation and revolution. The shape grammar developed reflects these possible classifications: it consists of two sets of rules, the first one for the design of the section (two-dimensional rules) and the second one for the generation of the volume (three-dimensional rules).

The study was developed in ten steps, as listed below:

Selection of the corpus of buildings;

Drafting their sections and modeling their volumes;

Grouping the sections and volumes according to common characteristics;

Drawing diagrams that explain these characteristics;

Establishing parameters (numerical and Boolean) for the definition of both sections and volumes;

Defining ranges of possible values for these parameters;

Defining the sequence of development of the compositions;

Defining the two sets of rules (2D and 3D);

Testing the rules;

Transforming the rules and generating novel designs.

The study is expected to show that the use of precedents in design does not necessarily result in a rigid style, but rather in family resemblances, which can be confirmed by the presence of shape rules.

4 Metodology

The major characteristic that these buildings have in common is the fact that their design is based on the extrusion or revolution of a trapezoid section. Unlike in Le Corbusier´s famous phrase, in this type of building the **section** is "the generator".

This two maior types can be grouped, according to their construction method: those with actual sloping planes (Fig. 2a), and those in which the sloping plane is just suggested by structural elements (Fig. 2b). Some of the buildings combine both sloping planes and sloping structural elements, thus characterizing a hybrid type (Fig. 2c).

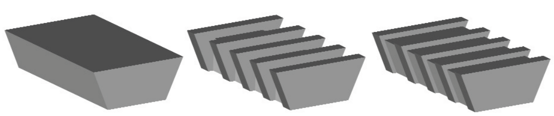

Figure 2: (a) Sloping façade planes; (b) sloping structure; (c) sloping structure and façade planes.

Another possible classification of the buildings is related to their volume, which can be generated by two different geometric transformations that can be used in the generation of the volume: translation (Fig. 3a) and revolution (Fig. 3b).

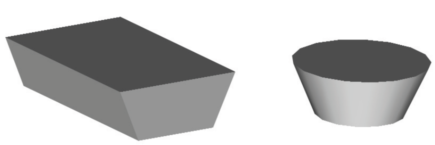

Figure 3: (a) Extruded volume; (b) revolved volume.

Despite these differences, it is possible to see that all the reserched buildings are somehow similar if we look at their sections. For this reason, the development of the shape grammar was divided in two parts: a set of 2D rules for defining the sections and a set of 3D rules for defining the volumes. Only the first part of the grammar is presented in this paper.

Not all of the building sections had a void space between the base´s two corners, as in Reidy´s Modern Art Museum. Some had a simple trapezoid section. Such was the case in Niemeyer´s CTA townhouses, Mendes house, Prudente de Morais Neto house, and ITA´s hangar - if we ignore the rounded corners of the later (Fig. 4a, b, c and d).

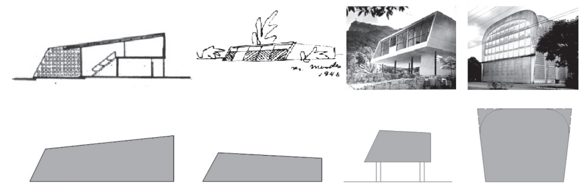

Figure 4: (a) Niemeyer´s CTA townhouses, (b) Mendes house, (c) Prudente de Moraes Neto house, and (d) ITA´s hangar.

Besides the different façade deflection angles and overall proportions, the major difference between these buildings is the fact that the three first have asymmetric sections while the later is perfectly symmetric. Another important difference between them is the fact that in the third section the trapezoid was placed above the ground level, at approximately 3m from it, while in the others it rests on the ground. In this case, the maximum height of the trapezoid is always multiple of a typical floor height (we will consider 3m here for simplicity´s sake).

The characteristics of these buildings were analyzed individually and a rule was defined for each of them, as described in the complete paper.

Conclusion

Although this is still a work in progress, this study is expected to show that it is possible to establish categories of buildings based on morphologic criteria, which can be confirmed by the application of shape grammar rules. It also proposes that the use of precedents in design does not necessarily result in a rigid style, but rather in family resemblances. Being able to recognize such resemblances is an important skill for both professional architects and architecture researchers. With this ability, one can establish relationships between different works, and one can also identify the influence of precedents in design.

The study will go on with the development of the 3D shape rules, the generation of all the reserched buildings by means of derivations, the adjustment of the grammar as needed, and finally its transformation, with the purpose of generating novel designs.

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From parameter to production

Alan Dempsey

Abstract

Do digital design tools merely facilitate ever more exuberant expressionism? Or do they contain a far more compelling potential for the avant garde that can ultimately radically redefine the architectural profession?

Using examples of current and recent architectural projects I have been involved with, I will illustrate how issues of formal expression, parametric constraint, and digital fabrication have been explored and dealt with and discuss how it has required rethinking the mode in which we traditionally operate as architects.

Keywords: architecture, parametric design, digital fabrication

Introduction

Over the last fifteen years digital systems have emerged as a primary focus of avant garde architectural design and research. Though it can be argued that contemporary avant garde production bears no apparent unity of aesthetic or formal logic, I propose there are three significant features common to digital parametric design that suggest we are in the early stages of a coherent movement that is at least as radical as the flourishing of modernism in the early 20 Century.

Firstly, digitally generated geometric and organisational forms can be characterised by a high degree of internal variation. Such variation may consist of elements, assemblies or surface variation but in all cases the transformation tends to be coherent and highly relational.

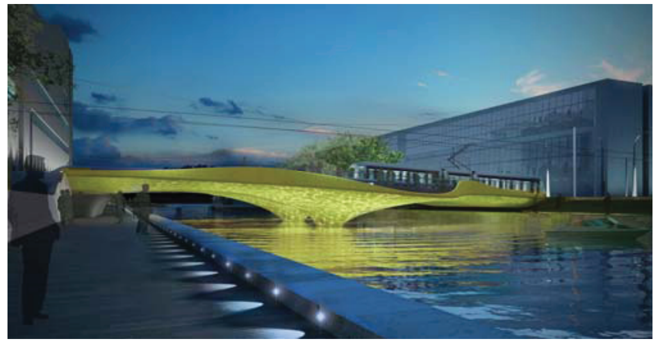
Secondly, the use of design models means that relational values are genuinely reciprocal and establish a system that can coordinate and optimise multiple design and production constraints. In addition, parametric models become the medium through which contemporary design teams interact and communicate.

Finally, digital fabrication technology is leveraged to economically manufacture these highly differentiated elements or components, and coordinate the information required to arrange complex assemblies.

To illustrate these issues I will discuss three architectural projects in which I have been recently closely involved. The projects are at significantly different scales and at different design stages providing valuable insights into how these issues can be addressed in differing ways.

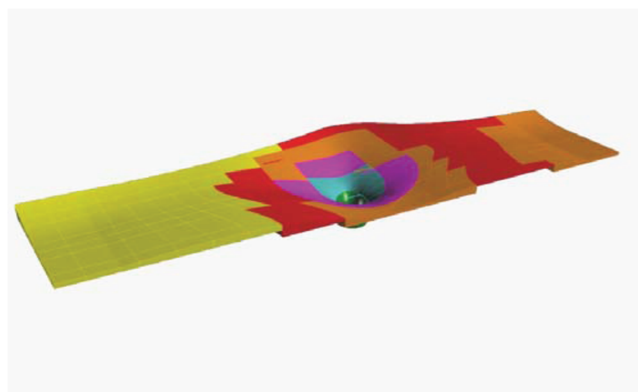
Spencer Dock Bridge, Dublin

The bridge is 40m span structure in Dublin City centre that carries road, rail and pedestrian traffic and explores the possible integration between urban infrastructure, public space and landscape. It is currently under construction and will be completed at the beginning of 2009.



view from canal

The bridge is a double curved curved asymmetric concrete structure which contains all traffic requirements and generous pedestrian walkways. The parapet edges of the curl down to reveal a tiered space for pedestrians to pause and enjoy the views of the canal and new parks on either bank away from the immediate vicinity of the road.



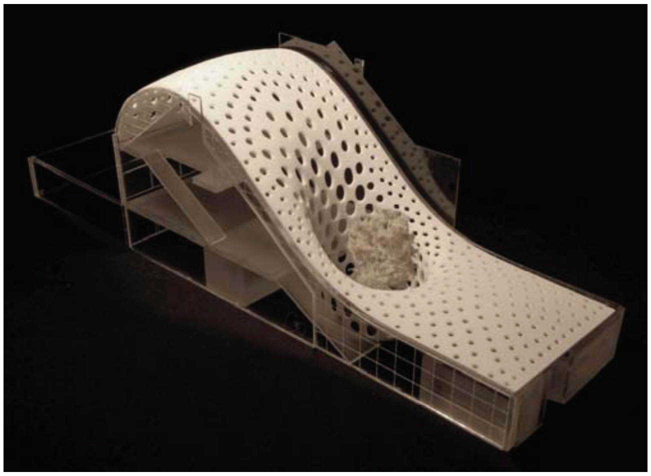
formwork layout

The bridge is being constructed from a combination of in-situ and precast reinforced concrete and all 1100m2 of formwork is manufactured directly from digital model files. I will discuss how this process was developed from initial sketches, how initial models were constrained and optimized, and some of the issues which arose during construction.

deck geometry

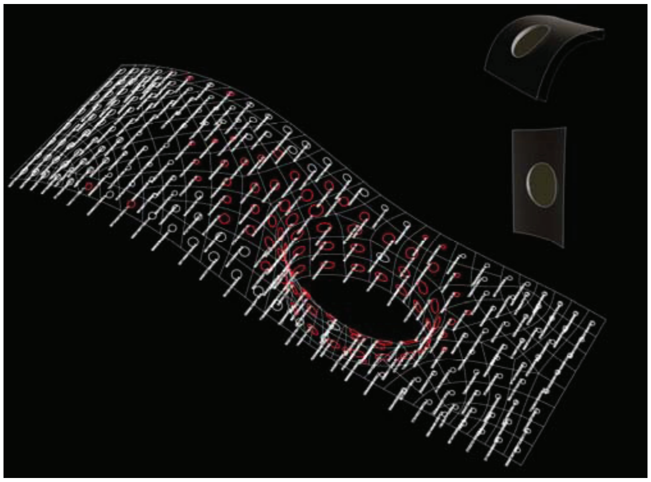
Clyde Lane House, Dublin

This project is a house for a furniture collector on an undeveloped infill site in central Dublin and is at the detailed design stage. The site is exceptionally deep and narrow and has a number of contextual constraints, most notably the required set back of the main mass of the house from the front boundary.



RP model study

The concept is to unite a number of different levels with a continuous perforated roof surface under which various pieces of built in and free standing furniture can be displayed with a high degree of flexibility. This roof surface also curves down to define an external courtyard located in the centre of the deep plan.



Parametric window distribution model

However, the complex roof geometry is not just a formal and spatial device but also regulates the environmental performance of the building providing day light, ventilation, and rain water recycling.

Close collaboration with the engineers has been required to develop a scripted parametric model to control the geometry, and distribution and orientation of openings according to structural stress lines, admission of daylight and surface water runoff.

Using the techniques developed for Spencer Dock, the roof shell will be manufactured directly from digital files in composite and glass before being delivered to site and assembled.

[C]space pavilion for AADRL10, London

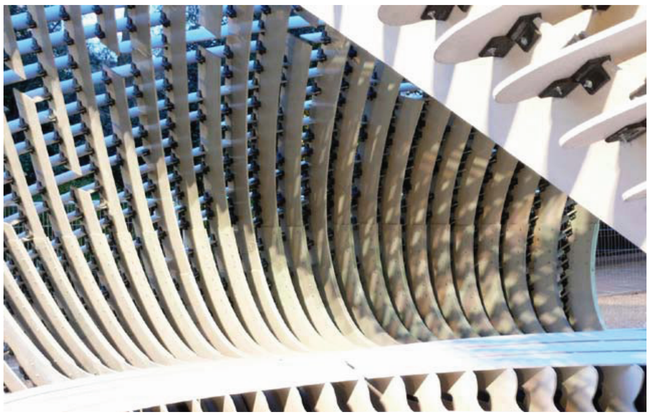
This pavilion was commissioned by the Architectural Association School for the tenth anniversary of the Design Research Lab and was completed in March. The project was the winning entry in a competition open to 354 graduates which required a small temporary structure manufactured from fibre reinforced concrete.

night view of completed project

The project progressed from sketch design to construction documentation in ten weeks and required intense collaboration with the structural engineers to develop a range of parametric models and scripts to quickly optimise the form, evaluate structural solutions and manage the final digital fabrication of over 850 unique pieces of concrete and steel.

day view of completed project

The success of the project has resulted in it remaining open in London until October 2008.



Detail

Conclusion

The projects described above clearly demonstrate the consistent recurrence of the themes I earlier identified. Specifically, that computational design allows for a high degree of internal qualitative variation that nevertheless remains coherent to a larger organising system; it further allows for the establishment of feedback between different constraints to introduce rigor and optimisation into a design process that is inherently more collaborative; and finally provides the means to economically control fabrication and assembly processes.

These changes to the architectural design process are so profound that they offer the opportunity to completely revitalise the profession of architecture by placing it once more at the centre of influence in the design and delivery process of architecture and urban design. However it also contains a warning that if we do not quickly adapt and take this opportunity, somebody else will and the role of architects will be marginalised even further.

Acknowledgements

[C]space pavilion was designed with Alvin Huang and constructed in collaboration with Yusuke Obuchi and AA DRL students.

Spencer Dock Bridge and Clyde Lane house were carried out in collaboration with Future Systems where I am a Project Director.

The Effects of Advances in Architectural Geometry on the Building Form and Structure

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Abstract

As Computer Aided Design has developed since the 1970s, it has enabled more complex building forms to be designed, drawn and constructed. The availability of complex curved surfaces has allowed architects, in particular, to design more expressive buildings (Howard, 2006). Complexity has also resulted in a more complex, curved and "free" architectural building geometry, which has been enabled by modern CAD tools (Penttilä, 2006). In contemporary architecture and structural engineering a trend towards the increased use of advanced geometry and computation can be observed. This poses new challenges for the structural engineer, the designed structures and structural types, and the technology used to design, describe, model, calculate, engineer, communicate, produce and assemble these structures (Coenders, 2006). The paper describes and examines the effects of the advances in architectural geometry on the building form and structure. It offers a possibility of a revised understanding of the relationship between architectural geometry and the building form and structure in the understanding of geometric concepts and approaches.

Keywords: architecture, geometry, CAD, digital technlogies, building form, building structure.

1 Introduction

In the last decade the attention of architectural designers and theorists has been primarily directed toward the descriptive geometries with which architectural space is written. To the extent that geometry is the preferred language for architectural communication, its interrogation has become the dominant form of writing in architecture. More precisely, the majority of both spatial and theoretical developments in architecture have become increasingly dependent on advanced geometry (Folds, Bodies and Blobs, 2008).

Digital architectures are profoundly changing the processes of design and construction. By integrating design, analysis, manufacture and assembly of buildings around digital technologies, architects, engineers, and builders have the opportunity to reinvent the role of a "master-builder" and reintegrate the currently separate disciplines of architecture, engineering and construction into a relatively seamless digital collaborative enterprise, thus bridging "the gap between designing and producing that opened up when designers began to make drawings," as observed by Mitchell and McCullough (1995) (Kolarevic 2001).

The new digital approaches to architectural design (digital architectures) are based on computational concepts such as topological space (topological architectures), isomorphic surfaces (isomorphic architectures), motion kinematics and dynamics (animate architectures), key shape animation (metamorphic architectures), parametric design (parametric architectures), and genetic algorithms (evolutionary architectures), as discussed in (Kolarevic 2000). New categories could be added to this taxonomy as new processes become introduced based on emerging computational approaches. For examples, new methods could emerge based on performance-based (structural, acoustical, environmental, etc.) generation and transformation of forms (Kolarevic 2001).

This study focuses on the effects of the advances in architectural geometry on the building form and structure.

2 The Effects of Advances in Architectural Geometry on the Building Form and Structure

Advances in architectural geometry have become instrumental in taking projects from a 3-D concept to reality. The intelligent 3-D model of the building or individual components can be sent to 3-D printers, used for cost estimating, shop drawings, and detailed coordination. This level of representation leads to enhanced understanding and commitment by all members of the client, design, and construction teams. However, the ability to apply the model directly to the construction process in either the manufacturing of components or formwork will be the most recognizable advancement of this new generation of buildings. This intersection of technology and environmental design will result in a range of architectural expression as diverse as the clients, sites, and design teams that create them. The following projects are examples of how far this multidisciplinary innovation is being pushed today and are intriguing representations of where the future may lead us (Byles and Oncina, 2008).

Figure 1: Al Hamra Firdous Tower, Kuwait City (Byles and Oncina, 2008).

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Skidmore, Owings & Merrill's Al Hamra Firdous Tower is a 412-meter-high speculative office building in Kuwait City, scheduled for completion in 2010. Its design is driven both by the needs of a developer - to optimize the value of the property - as well as the context of the building's environment (figure1 and 2) (Byles and Oncina, 2008).

Figure 2: Structural frames in Al Hamra Firdous Tower, Kuwait (Byles and Oncina, 2008).

The project team used two digital modeling software programs — Rhino and Digital Project — in addition to AutoCAD. Rhino, a program the team was already familiar with, was used to create basic massing models of the tower quickly. Unlike Rhino, Digital Project is parametric modeling software that allows designers to establish relationships and set key parameters; this was employed in areas of particular geometric complexity and where issues of iteration and testing were anticipated. While it is conceivable to use Digital Project to design entire buildings, SOM used Digital Project to execute the design of a few key areas efficiently (Byles and Oncina, 2008).

Isomorphic architectures (Figure 3), based on isomorphic polysurfaces, represent another point of departure from Platonic solids and Cartesian space. Blobs or metaballs, as isomorphic polysurfaces are sometimes called, are amorphous objects constructed as composite assemblages of mutually inflecting parametric objects with internal forces of mass and attraction. They exercise fields or regions of influence, which could be additive (positive) or subtractive (negative). The geometry is constructed by computing a surface at which the composite field has the same intensity – hence the name – isomorphic polysurfaces. The surface boundary of the whole (the isomorphic polysurface) shifts or moves as fields of influence vary in their location and intensity (fig 3) (Kolarevic 2001).

Figure 3: Isomorphic architectures: Bernard Franken's BMW Pavilion in Munich (Kolarevic 2001).

The production strategies used in 2D fabrication often include contouring, i.e., sequential sectioning (Figure 4), triangulation (or polygonal tessellation), use of ruled, developable surfaces, and unfolding. They all involve extraction of twodimensional, planar components from geometrically complex surfaces or solids comprising the building's form. Which of these strategies is used depends on what is being defined tectonically: structure, envelope, a combination of the two, etc (fig 4) (Kolarevic 2001).

Figure 4: Structural frames in Frank Gehry's Experience Music Project in Seattle, produced by contouring (Kolarevic 2001).

Free and unconventional digital experiments, such as imaginary design project proposals in competitions, sometimes also leads to "iconic"3D-artifacts, which have artistic value even as themselves. Good modern examples of digital-deconstructivistic and fluid, free-form architecture of virtual projects are for example shown by the recent works of Greg Lynn and Kivi Sotamaa (fig 5 and 6) ((Penttilä, 2006).

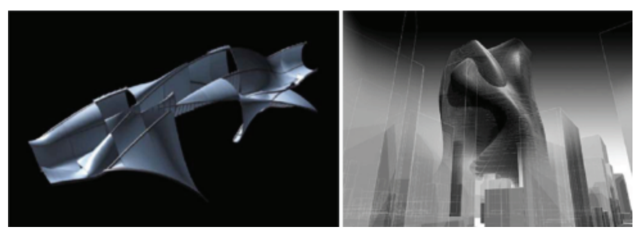

Figure 5 and 6: (left). Projects from Greg Lynn Form and Kivi Sotamaa/Ocean-North. Fig. 6: (right) (Penttilä, 2006) .

Complex architectural forms and shapes make on-site building erection more complex, often unconventional, and surely innovative. Unfortunately it is also more expensive than erecting simple rectangular buildings. Design-CAD with computer-aided manufacturing tools has anyhow made it possible and much easier to produce free form geometrical architecture, as Branko Kolarevic states (Kolarevic 2001).

The high-end 3D-modelling and visualization used in complex-geometry construction projects has in its most enhanced cases had also a strong connection with current digital production technologies, such as building component prefabrication, the links from 3D-CAD-models to automated manufacturing (CAD/CAM) and computer-numerical-controlled production, CNC-tools (Penttilä, 2006).

Geometric conceptualization has always been among the essential mental tools required for the invention, modeling, and visualization of spatial building structures. Furthermore, without an understanding of the geometric and mathematical base of computer graphical procedures, the ability to cope with significant developments in advanced architectural graphical representation and to adapt to the ever-changing technology in this area is limited. Although these technologies have many features for the modelling the geometrical representation of a structure, buildings consist of more than only geometry and generation. For free-form structures, surfaces should be meshed, tessellated or populated to impose a grid-based structure consisting of these parametric elements. However, not all restrictions of the structural design can be expressed in a single surface model of the intended design, since often the structure imposes restrictions in the form of angles, lengths, stresses, etc (Coenders, 2006).

Conclusion

New technologies, such as the capability of CAD systems to handle complex geometry, have often been use to extend the possibilities of design. Ideally, while better production processes are becoming more widely applied on conventional buildings, their use on the more complex forms that are now achievable, will also be developed to provide the richness of complex forms and the efficiency of integrated design and production methods (Howard, 2006).

Building product modelling may well be one of the major trends to manage complex building projects in an integrated way in the near future. Since CAD-systems have been very essential tools to produce and maintain the geometry-based building data throughout this described evolution, the management of current building activity with concurrent design and engineering is not even possible without CAD-tools any more (Penttilä, 2006).

We are able to work more collaboratively across disciplines than ever before because the advances in architectural geometry are blurring the boundaries between architecture, engineering, the sciences, and technology. In the future, the success of architecture will be measured by how well buildings respond to the needs of their inhabitants and culture with innovative solutions that also protect the environment (Byles and Oncina, 2008).

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The Role of Architectural Geometry in Performance-orientated Design

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Abstract

Architectural geometry continuously gets reinterpreted by manifold parties during the design process. As a building project progresses it does so through constant input by a variety of designers and consultants. In recent years, performance orientated design has become increasingly important and with architectural geometry as interface between all building-performance related design aspects we are faced with new challenges. This paper presents an analysis of the current situation for sharing 3D geometry models amongst various members in the design team and it highlights some of the constraints for geometrical interoperability. The authors then propose three concepts for integrating and representing geometrical aspects of building performance across disciplines.

Keywords: transdisciplinary design, performance optimization

1 Introduction

A building's geometry embodies an unlimited set of requirements about (inter alia) programmatic, functional, aesthetic, technical and environmental aspects. Geometry is in that sense representative of a certain aesthetic as much as it is reflecting functional necessities and performance constraints. Priorities between these criteria have constantly shifted in architectural history depending on function, cultural particularities, predominant styles, the availability of construction materials, the skill and technology level and climatic constraints. In times of global warming we currently experience a shift in thinking. Responding to sustainability issues of our built environment we now explore the geometrical expression of buildings as pivotal for various types of building-performance over their whole lifecycle. As a consequence, the design of buildings becomes more process and performance orientated. We need buildings that sensitively respond to geographic, ecological and economical constraints of their local surroundings and we need to find ways to allow designers and consultants from various fields to share their geometry models from the early design stages onwards to test building performance across disciplines.

2 Analyzing the current situation

A closer look at 3D geometry models currently used by architects will reveal that in most cases they are one way streets. They are tailored to communicate architects' design *to* others instead of communicating it *with* others. A similar argument can be made for models used by building consultants. What are the reasons for this?

In traditional work-methodologies designers and consultants have interacted on the basis of 'abstracted' representations of their work in two dimensional plans and sections that were handed over to design partners. Over the past two to three decades this has changed with the increased availability and use of 3D digital geometry. The drivers for the transition from 2D to 3D are manifold; whereas architects have embraced them first as a means to visualize their designs in the most realistic way, consultants have embraced 3D geometry to carry out different types of analysis, design documentation and even construction and facilities management. With all on board the 3D train, there seems to be a lack of coordination and synthesis between the different parties and we are not as yet tapping into the full potential of integrated 3D work-environments. The 3D geometry model provided by the architects often does not contain the right information to enable engineers to carry out their performance analysis. 3D engineering-analysis results are often not easy to integrate in design documentation, etc. In addition to that, there are varying requirements for geometrical information from the different engineering disciplines and sometimes even within one discipline when using different tools. New industry standards such as Building Information Modeling (BIM) are addressing this issue, but often fail to offer solutions for the earlier design stages when smooth information exchange between different partners has the strongest impact on the final result. Laiserin goes raises the argument that the fragmented state of model and file-format incompatibility is the biggest shortcoming of BIM today as linkages between models from different disciplines cannot be taken for granted. (Laiserin 2008)

3 Constraints for Geometrical Interoperability

Why is it difficult for consultants to use models by others in the early stages of design, why do we constantly need to re-interpret the same design information?

There are at least three principal obstacles in the sharing of 3D geometry information between architects and consultants. First there is a liability issue. The author of any geometry file cannot be held responsible for the correctness of the data intrinsic to his/her model beyond the immediate purpose assigned by the author. As 3D geometry models are used for testing different aspects of the building's design, information has to be checked and possibly reworked by others to ensure the validity of the information for their own purpose. The second obstacle is the translation problem between different software packages. It results in errors during transfer between proprietary software tools as geometric entities are often defined in different ways. The third obstacle relates to the selection requirements of consultants for addressing the exact type of geometry needed to analyze the part of the design they are responsible for. While the first two obstacles are currently heavily debated in building research and practice, this paper will focus on the geometry types required for information exchange.

Can we categorize types of 3D geometry required for various analysis purposes? To what degree does geometrical data have to be simplified or even be redrawn to suit specific analysis purposes? How does this vary from group to group and their according tools? A common problem in the setup of geometry models for analysis purposes is the issue of 'defeaturing'. Whilst 3D geometry models for architectural representation require a high amount of detail to display visually correct information, analysis models for most building performance requirements need to be stripped of such detailed information. Not only would it be unnecessary to include that information in a model, it would also increase the time needed to analyze a model exponentially and sometimes even produce incorrect results. The scale in which the ‘defeaturing’ process has to take place can be problem and discipline specific. Another method applied by designers and consultants is ‘equivalencing’. This is not so much an issue of scale and detail, but a necessary simplification of geometrical entities with an equivalent that holds information representative of that entity. The process of equivalencing is highly profession specific and each it represents knowledge-based information resulting from precedence studies.

3.1. Structural Analysis

The most common way for structural engineers to build up their geometry models is to define the centerlines of geometrical objects. In contrast to architects who represent the outer boundary of building elements such as columns, beams, walls or similar, structural engineers abstract geometric objects as simple centerlines and attach a thickness or predefined section types from a library of structural elements to them.

Figure 1: Structural centre-line model

Structural systems are represented as a network of interconnected centerlines for conducting member-size optimization and code-checking (Figure 1). The important aspect for structural engineers is the load that applies on the (nodal) connection of members and the stresses that occur within the members. For this purpose, structural engineering software has the capability to interpret networks of interconnected nodes as surfaces in order to equally transfer distributed loads (such as wind-loads) to their neighboring nodes. In some cases engineers conduct finite element analysis (FEA) of surface models to analyze local stresses in the material. In this case, any shape of the underlying building-geometry can be used and imported into structural engineering software as Nurbs surface-model. It then gets subdivided into a mesh of (finite) elements that individually are analyzed in a consequent process. Depending on the base-type of element used for the mesh, it can approximate any 3D shapes to high levels of accuracy. The general level of accuracy for structural analysis models is depending on the design stages. Whereas structural engineers approximate their models in a range of about 100mm in the earlier design stages, a high accuracy of their 3D geometry models becomes essential towards the later design stages where they often operate with mm precision. The level of required accuracy is also depending on the structural material in use. Whereas concrete structures allow for tolerances of up to 30mm, steel structures would only allow for tolerances up to 15mm or less.

3.2. Building Physics

Building physics modeling for environmentally sustainable design can be divided in three sub-categories: Thermodynamics, lighting analysis, and fluid dynamics. All geometry models used for thermodynamic analysis have to be closed (watertight) because thermal modeling is all about zones. A zone is defined hierarchically by sub-surfaces. Computational energy analysis software then needs to know about the overall volume individual surfaces enclose and how they relate to each other to simulate radiant heat-transfer. Software for the evaluation of thermodynamics will calculate for each hour during daytime how much sun is coming through windows that are associated with a zone. After the user defines zones the thermodynamic analysis software can auto-detects the volumes by spraying rays around the place from certain points finding out where the enclosed regions are.

Depending on the software in use, non rectilinear elements of the underlying building geometry have to be simplified into block objects to allow the thermodynamic analysis to be carried out. A sloping external wall would have to be reinterpreted as stepped block wall through manual input. For setting up geometry models for thermodynamic modeling on the exterior of a building, surrounding buildings need to be included in the model with their exterior walls drawn as surfaces to analyze overshadowing. Features that are smaller than ½ meter for walls or about 200mm for particular small scale elements do not get included in the model. Depending on this scale, some external shading devices do not get drawn, but they are abstracted as virtual surface representation. This is a process of equivalencing. Instead of drawing 20 horizontal slats one generates one equivalent vertical shading surface with a transmission factor.

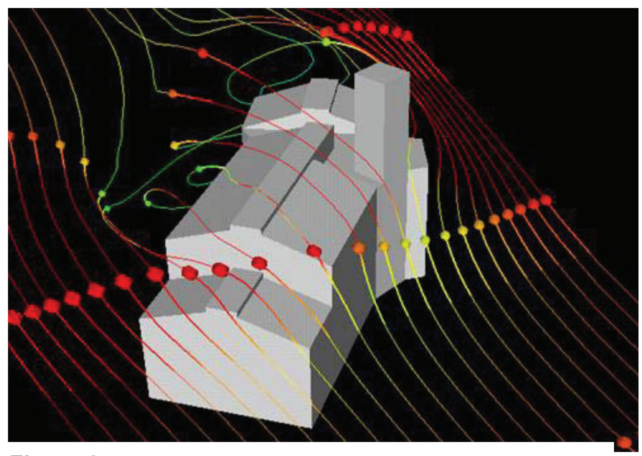

Figure 2: External CFD model

For computational fluid dynamic analysis (CFD) in the interior of buildings, internal volumes are used that can be generated out of surfaces models of the inner layer of walls. Software tools for CFD can handle just about any CAD to create meshes from surfaces plus curves plus points. The meshing function in the software identifies these corner nodes and moves them to the nearest geometrical entity it can find. If the user defines a particular point that needs to be captured in the mesh (like a pointy end), the CFD mesh knows is has to go there. CFD meshes represent unstructured meshes unlike meshes for fire modeling FDS which use Cartesian mesh and it can only be xyz orientated and the users ends up with steps.

For exterior fluid dynamics modeling a mesh is wrapped around the outside of buildings to create an atmospheric boundary lattice. As exterior models are often investigated on an urban scale, the lattice grid is much coarser than the grid used for interior (Figure 2). Internally the issue of equivalencing becomes highly important: It is tested how air is moving around in interior spaces given the presence of a range of diffusers (such as air conditioning units or similar). If the CFD grid-size is 200mm and diffusers are of a smaller scale which is very common, they would get lost when creating the grid even though they are vital features for the analysis model. One could taper the grid to address this issue, but there is a limit to how fast a grid can 'grow' and transition cells in the grid are required. Given the high amount of diffusers per project, one has to equivalence them with something that behaves about the same way and allows the user to implement a large grid.

Most software used for our lighting analysis works on geometry built up from a planar polygonal-mesh. Thicknesses of walls including the interior wall-surfaces are not represented in the geometry model, but their buildup and material-properties are specified in associated material-libraries. A specific material is associated each polygon or group of polygons and the computational lighting software calculates how the light is distributed. If geometry is important from external sources, the direction of surface normals needs to be checked to make the software distinguish interior form exterior planes if they have materials with different front and back properties Results are either plotted back through coloring the geometrical entities in the 3D model, or they are plotted in a graph/spreadsheet. 3D geometry models for light analysis require the least kind of hand-holding and one can at times use the 3D model that comes straight from the architect.

3.3. Acoustic Analysis

3D geometry models for Acoustic optimization and auralization is applied for testing the acoustic properties of interior spaces such as auditoria, meeting rooms, concert halls, and foyers. They are set up as coarse representation of the inner surface areas of a particular space for broad geometrical shaping or to simulate reverberation times from sound sources to their surrounding surfaces (Figure 3). The level of detail included in acoustic geometry models can not be defined uniformly as it depends on the frequency-range that is being investigated. Some acoustic-specific features such as deflection –screen need to be included in the model and represented with all their surrounding surfaces to ensure sound 'bouncing; off them in the most accurate manner.

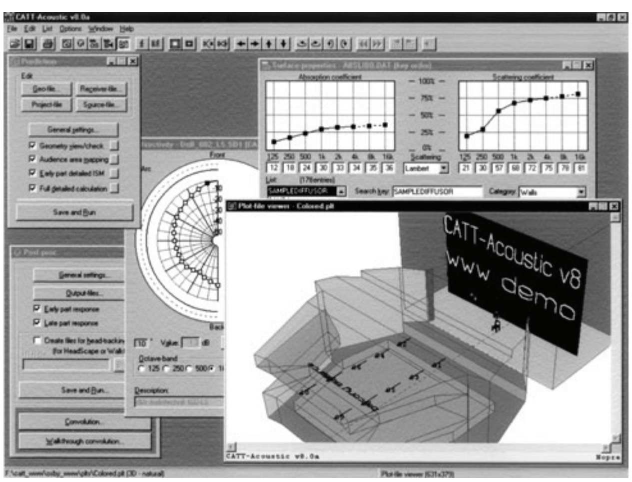

Figure 3: CATT® Acoustic v8 modelling interface

3.4. Fire Engineering

Models for fire engineering are used for analyzing three main problems: The most common aim is the analysis of smoke-spread within building using fire dynamics simulation (FDS) on the basis of computational fluid dynamics (CFD) to study air/smoke movement over a certain period of time. The second type of analysis done for fire engineering is 'egress modelling' to study people-movement within - and out of a building in the case of fire, and the third type of analysis are simple tests for understanding heat-flux using radiation modelling. Whereas egress models do not require much appropriating of architectural models for their use (the analysis mainly needs to understand geometrical boundaries for escape-routes), smoke movement analysis works on a different principle. Geometrical entities are either generated or (if imported from a third party model) subdivided on the basis of a user-defined grid that depending on the granularity of the information required for CFD analysis and the available computing-power. In order to analyze smoke movement within a building, fire engineers use the interior surfaces of a room to define obstructions in their 3D model that prevents smoke from spreading. Buildings are then set up as a series of connecting surfaces that get interpreted as volumes by the analysis software. Between the volumes there are interconnecting openings for doors and planar elements that sit flush with the wall representing vents such as windows or mechanical piping. The wall thickness of the boundary surfaces of a volume is defined in the geometry model, according to the minimum requirements of the grid as seen in Figure 4.

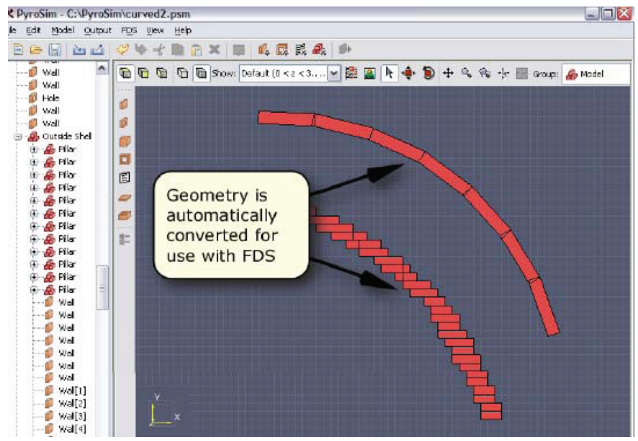

Figure 4: PyroSim®: interpretation of geometry

Problems in the appropriation of third party models occur if surfaces in the geometry-model have been drawn using non planar surfaces such as Nurbs-based geometry. The smallest size of geometric objects in the model should exceed 300mm in order to enable standard grid-sizes to pick them up. Depending on what is to be analyzed, the fire dynamics simulation model can also include objects in the interior (such as furniture) that have an effect on the smoke-movement.

4 Integrating and representing building performance across multiple disciplines

How can we transgress profession-specific thresholds to share 3D information across software platforms and teams in the early design stages in spite of their different geometrical requirements? How do we avoid re-creating information that has already been produced by others? From the detailed description presented in the previous chapter we can draw the conclusion that one singular 3D geometrical building representation is not sufficient for multi-objective performance evaluation. There are certain similarities between some of the models – in particular for thermodynamic, fire and acoustic analysis, but at the same time substantial differences exist as well.

We propose three potential methods to integrate the geometric information and then compare analytical results from across discipline boundaries. These methods range from disconnected, independent models, through to highly connected models in which outcomes of design scenarios are influenced by informational dependencies between these models.

4.1. Disconnected geometries, independent analyses

Making use of the proliferation of CAD viewers and file exchange formats, it is possible to co-ordinate geometry across independently created discipline specific models. This would provide designers with a way of graphically comparing their analysis model to the current 'master geometry' in order to highlight major differences between the models, even if the geometry of the underlying models cannot automatically be reconciled (e.g. coarse vs fine details, surface vs solid). Downsides to this approach are that designers are often forced to view their model in unfamiliar software, whilst changes to the geometry are manually made in the native analysis software. Also where a CAD viewer cannot natively import geometry from the analysis package, the 3D data must first be transferred through an intermediate format, increasing the chance of inconsistencies.

Once discipline specific analysis is complete, building performance as a whole can be judged. Recent advances in the tools available to create real-time, interactive 3D visualizations and 'visual programming' (Vande Moere 2007) have lowered the barrier to creating custom environments for designers to discuss multi-disciplinary design. Tools such as Quest3d®, MAX/MSP® and Virtools® provide two important capabilities to support this: Firstly the ability to import and represent architectural geometry in 3D. Secondly these tools enable design teams to import and represent the data which forms the results of various types of analysis. These 'results' may take the form such as accurately rendered surface texture, based on site-specific lighting conditions, or additional 3D entities in the model such as a field of animated arrows to visualize results such as airflow, or acoustic reflections for synchronous design-evaluation. (Weinstock and Stathopoulos 2006), (Woodger 2006)

4.2. Connected geometries, independent analyses

In order to enable greater exploration of the design space, routine operations such as the updating of underlying geometries should be as automated as possible. Parametric, associative geometry software offers a solution here, potentially providing ways to setup a master geometry and link discipline specific analysis geometry representations to it. This would not automate the processes of 'defeaturing' or 'equivalencing', instead allowing the discipline specific modeller to decide how to model their geometry, and how it relates to the overall whole. It is then possible to push geometry changes from the master model into a discipline specific analysis model, situated in the desired analysis software, reducing the amount of 'rework' each time a new geometry is proposed.

The use of parametric, associative software also invites architects and designers to formulate their geometry in terms of parameters as 'key geometry drivers'. In this way the master geometry becomes a negotiation tool as it gives designers the opportunity to propose design variations based on those parameters. In this way 'geometry cases' can be developed similar to the way 'load cases' are used by structural engineers to test their models for varying boundary conditions.

As the results of these 'geometry cases' are collated, they can be used to generate variations of the project-specific design evaluation environment. For some analysis types trends can be observed by .using Excel® spreadsheets to map how changes to the 'key geometry drivers' affect the numeric analysis results.

4.3. Connected geometries, interdependent analyses

A step further is the setup of a collaboration framework which supports bi-directional exchange of 3d data and analysis results, with a graphic user interface for common 'sense-making' and decision support. Such a framework will accommodate ways for impacting building-geometry through outcomes of engineering-analysis and they will require common data-storage as a repository for project information.

Based upon the same concept of a master geometry hosted in parametric/associative modeling software, this method includes a feedback loop such that the results of an engineering analysis can be re-interpreted as a potential input for automated changes to the 'key geometry drivers' (Holzer, Tengono and Downing 2007). The interpretation of the analysis results, and the effect they have one the 'key geometry drivers' is determined by processing a series of rules hosted within the collaborative framework application. These rules are authored by the design team, encapsulating discipline specific suitability criteria and their relationships to the 'key geometry drivers' upon which the design is based. This allows the computer to perform semi-automated exploration of the design space without the design team giving total control to the computer. Important aspects of this 'collaboration framework' include the ability to store both geometric and non-geometric data in an independent format (such as the extensible markup language XML) and also the ability for analysis applications to be 'driven' by the controlling framework application.

Conclusions

Although working on the same project, the various parties reliant on 3D architectural geometry for testing the specific performance of a design often work on substantially different interpretation of the underlying building geometry. Each profession depends on a specific set of geometrical constraints to make their analysis function in its given context. In spite of all the differences in modelling and editing of geometrical entities, there are several ways of linking geometries to design analysis either independently or interdependently and to reference geometry-cases to according analysis cases. In addition to the methods described, coordinating 3D geometrical models might require a person acting as 'centre-point of information' who needs to be able to understand, integrate and manage various sources of architecture and engineering.

Acknowledgements

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Spatial and Sectional Geometry of the Bearing Structure of the Open Theater at Hellenic World Foundation Complex in Athens

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Abstract

The open-air theater (images 1, 2) is located in the southern side of the `hill-building' that accommodates the Research Centre (R-C) and it is connected functionally and structurally with it. Both are parts of Cultural Centre "Hellenic World", according to the master plan that was developed from the architectural office "Anamorphosis" which has also the responsibility of planning of the above-mentioned structures. The exterior outline of the theater, does not have fixed distance from the centre. The theater's width is maximized in the region that it is connected to R-C building and afterwards decreases progressively.
Keywords: architecture, design and fabrication optimization in construction

1 Introduction

The Cultural Centre "Hellenic World" was envisioned by the Administration of the Foundation of the Hellenic World and was designed by the architectural office "Anamorphosis". The design philosophy of the total complex is inspired by the Greek History and Mythology. Thematic forms based on the human scale and the Greek landscape that is characterized by its slops, caverns, lakes, gorges, the sea and its flora, are provided. In the framework of this design philosophy, the R-C building optically reminds of a volume of a geological shaping. The western side gives the impression a reverse geological crack, while the eastern is a smooth slope covered with plants and threes which can be approached from the surroundings . Finally southern side takes concave shape in which the open-air theatre is formed.

2 Spatial Geometry of the Theater's Bearing Structure

The theatre has been divided in 30 sectors via 31 axes. These axes have actinic addresses and separate the surface of theatre in sectors with epicentral angle of 7.05^o up to axis 10. After that this angle gradually decreases by 0.05^o and it becomes 6.50^o at the 26^{th} sector. After this sector it increases by 0.5^o and it becomes 7.50^o in the final sector.
As the radial distance of the outline of the theatre is decreasing, the requirements for rigid supports are also decreasing. In order to satisfy the static demands, three sets of interrelated supporting arcs have been chosen.
The set arcs A is the nearest to the centre of the theatre and it appears in all axes 0~30. The immediately next set of arcs B appears in axes 1~26. The final set of arcs C appears in axes 2~16. Specifically in axes 3~10 the arcs of set C are connected to the R-C building. Via this connection the bearing structure of the theatre contributes in the stiffness and torsional rigidity of the building against static and dynamic horizontal loads. From the point of view of the topology the interrelated arcs are distinguished in 4 groups as the are shown in the fig.1.
In order to satisfy all architectural and static requirements, a treatment of data was conducted using simple mathematic relations which resulted to:
- The spiral orbits from which the arcs emerge.
- Their centres and their beams of curvature.
- The arcs and their points of contact with the envelope of the seats.

The bases of the arcs lie on spirals traces all of which have the centre of the theatre as a starting point. For the internal bases of the arcs A, B, C (fig.2), the spiral trace runs an angle of 4π from the start point up to the axis 1. For the exterior base of the arc B the angle is 5π , while for the exterior base of arc A it results to ~3π up to its initial axis 10. (fig.3).
By using the above mathematic treatment not only the initial objectives were achieved, but also resulted in linearly or evenly varied values for the following geometrical entities:
- The radius of curvature
- The vertex of the arcs
- The distances of the centers of the arcs from the starting point of the spirals
- The tangents of the arcs at the points of emersion

The smooth change of all the above entities elements appears in fig.4

3 Sectional Geometry of the Theater's Bearing Structure

In the same spirit of aesthetics, constructibility and static efficiency the cross-sections of arcs were designed. For each set of arcs, specific cross sections have been chosen (e.g. arc's vertex for arcs B and C, connection with B for arc A) where the width b and height h have standard values. These values vary linearly along each arc with constant rate for each set of arcs. Some of the arcs have a

In certain arcs a channel is provided at the lower flange for the installation of lightning bodies (fig. 5). The tube is filled with concrete and enforcing bars and laminas are provided to avoid local buckling in the lateral webs (fig. 5).

Conclusion

A close collaboration among architects and structural engineers took place, in order to optimaze the aesthetic the constructibility and the static eficiency of a structure aiminig to contribute to the culture.

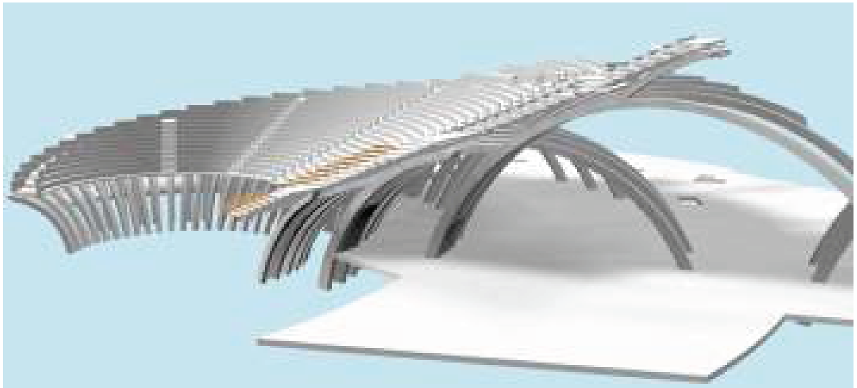

Image 1: Open Theater – Side view of the bearing structures

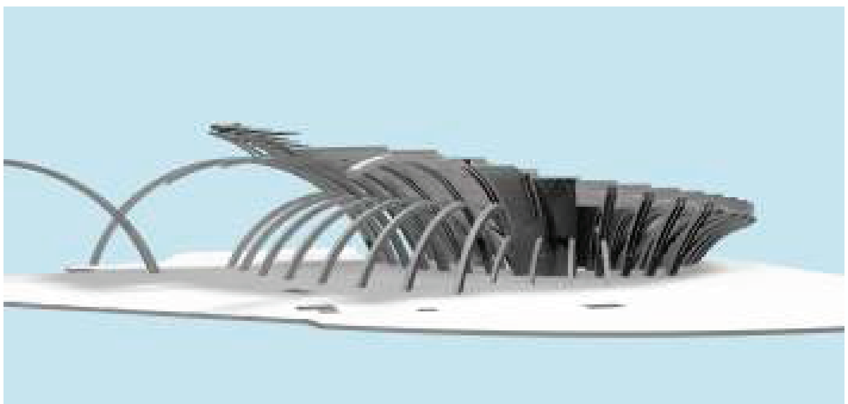

Image 2: Back view of the open theater

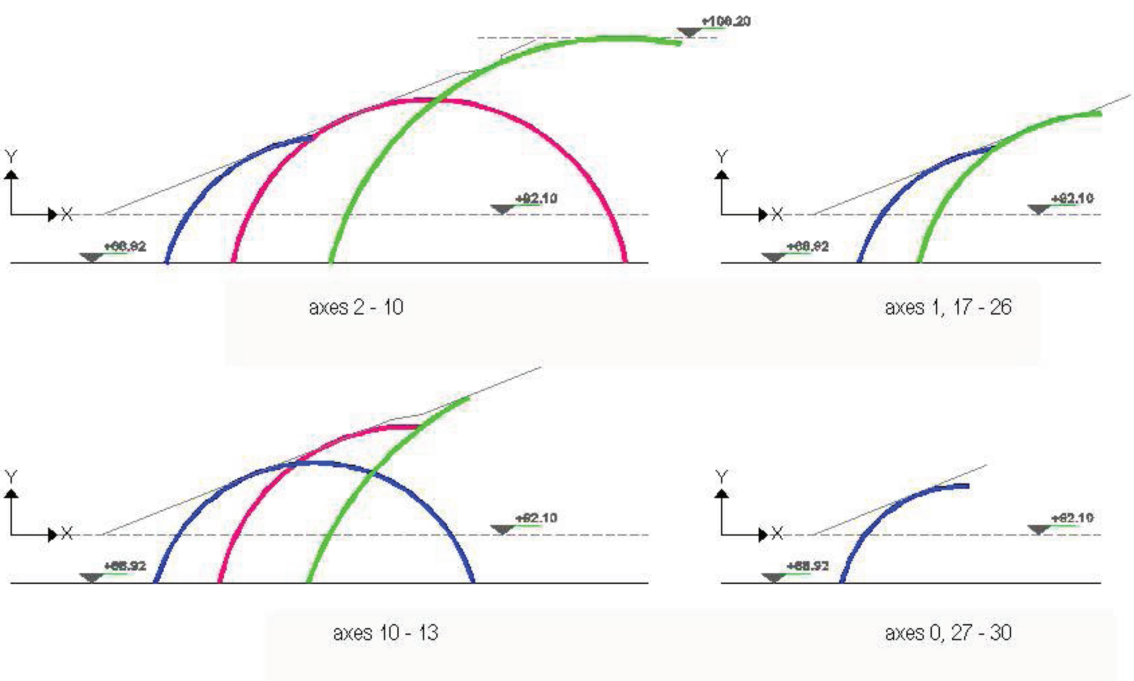

fig. 1: Topology of interrelated arcs

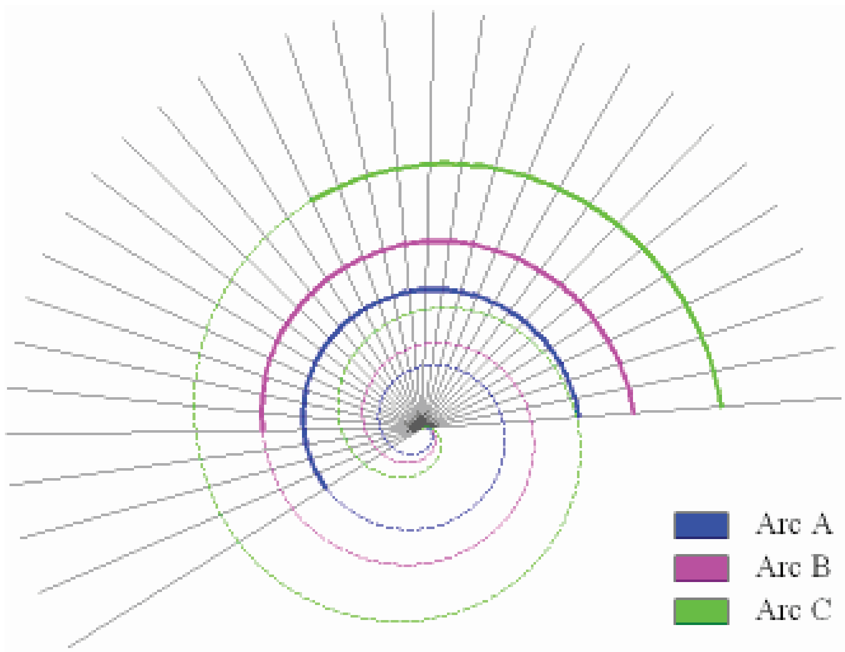

fig 2: Spiral traces connecting the inner bearings of the arcs

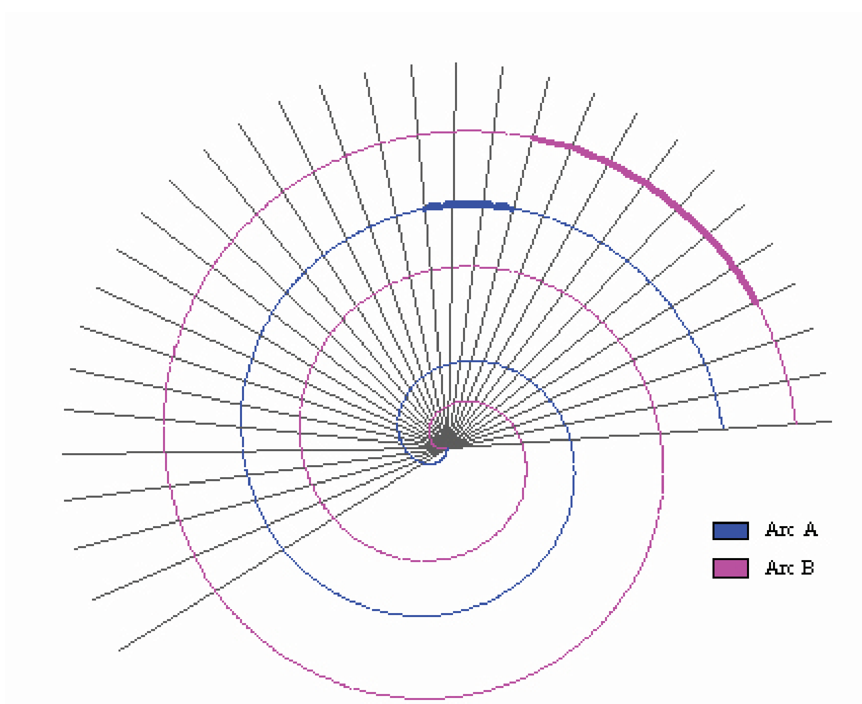

fig 3: Spiral traces connecting the outer bearings of the arcs

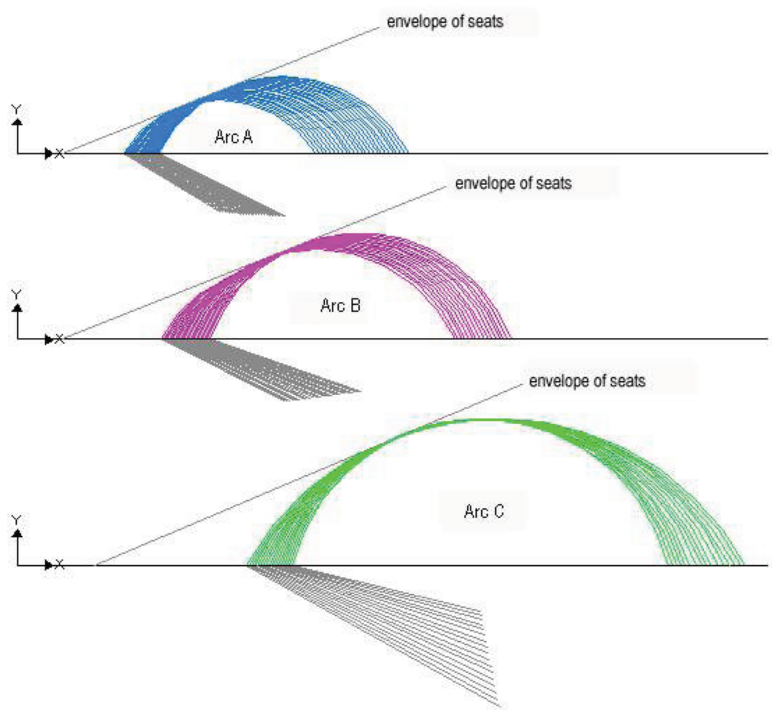

fig 4: Positions of centers – Radius of curvatures - Arcs

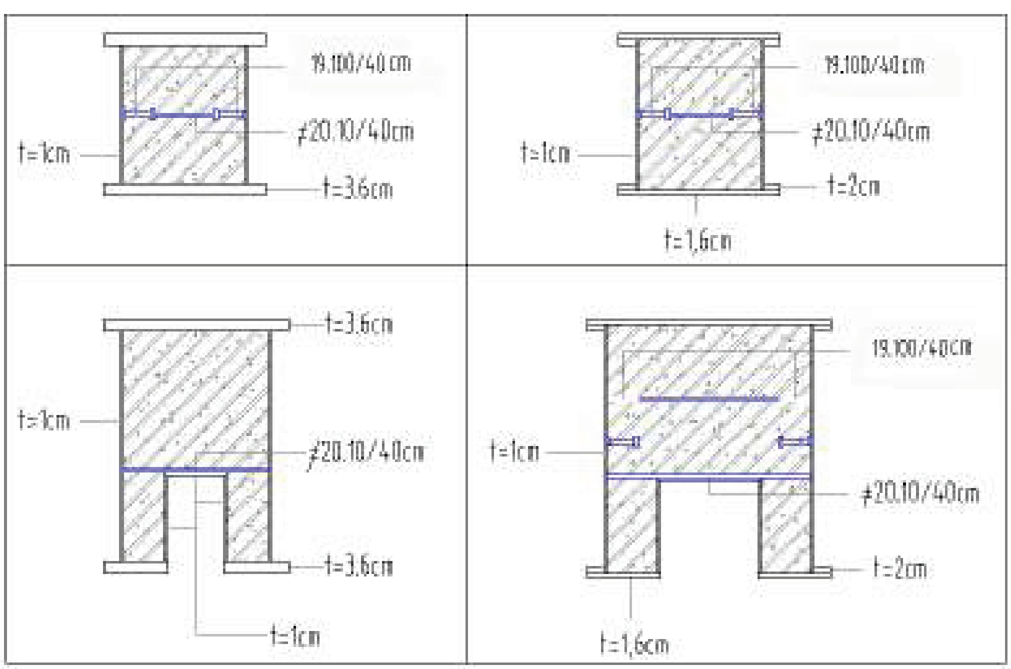

fig 5: Indicative composite cross-sections of the arcs

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Abstract

Structures the form of which belongs to the general class of helical surfaces have found a broad application in buildings of all times. Historical and contemporary examples of helical structures cover a wide morphological array that primarily results from the spatial transformation of the basic geometric features of helical surfaces. A double layer helical surface is a morphological variation the geometric construction of which has to integrate the method by which the structure is "doubled". This paper investigates the possibility of constructing a double layer helical surface structure from the assembly of tensegrity modules. A brief discussion of the criteria and assumptions made, the observations on their geometry, and the proposed methodology are also included.

Keywords: modular tensegrity structures, helical surface

Introduction and questions on the geometry of helical surfaces

The general class of helical surfaces has found a broad application in structures and buildings of all times. Twentieth century celebrated structures such as Tatlin's Tower and Bruce Goff's Japanese Art Pavilion share basic geometric features with a large array of modernist and contemporary structures of various scales. The helix' indefinite growth, that both alludes to symbolic interpretations at the conceptual level of a design project (Nekromanteion of Acheron - Ancient Greek funerary monument), and/ or to programmatic and functional requirements (Guggenheim Museum of Art), probably accounts for the extensive use of helical geometry in building design. Yet, regardless of the motives that have led to the form of a helical surface, from the initial geometric conception of a helical building to its realization, one can trace numerous intermediate configurations; very often these are directly associated to transformations of the initially conceived helical geometry to respond to technological requirements and limitations.

From a purely morphological point of view, one can distinguish two basic categories of helical building structures: a) those that can be described as continuous or developable surfaces, and those perceived as discrete configurations of a helical surface. In general, when a discrete helical surface is considered, in addition to the basic geometric principles that apply to all helical surfaces, other new rules need to be defined and implemented. The new rules have to take into account the method used to develop the patterns of discrete elements on the surface of the helical surface and the extent to which these patterns relate to the basic geometry of helical surfaces. Following this line of thought, one could also consider the reverse geometric problem; that is, once a geometric shape or pattern is given, to determine whether and how this pattern can populate a helical surface and whether a helical surface tessellation is possible.

Similarly one can distinguish between single layer and double layer helical surfaces. A double layer helical surface is a morphological variation with frequent application in building design. When comparing its geometric features to the features of its single layer counterpart, it becomes obvious that additional information is needed with regard to the method by which a helical surface can be "duplicated.' Respectively a geometric construction process that integrates this method needs to be established.

Combining the features of discrete helical structures and those of double layer helical structures, one can consider populating a helical surface with 3D elements composed of linear members to form a double layer helical surface. Eventually when the 3D elements are regular or irregular polyedra, the question leads to a new problem which could be described as "space packing of polyhedra on a helical surface" and requires determining new rules, conditions and constrains based on both topological and numerical relationships.

Departing from the above questions and problems, this paper investigates the possibility of constructing a double layer helical surface from the assembly of tensegrity modules. The assumptions made, the developed geometric rules , conditions and constrains that have made possible the construction of a helical tensegrity structure are described in the following sections.

1. Double layer helical tensegrity grids: Geometric assumptions

Adopting a modular conception for the development of a helical structure is in principle directly related to the main geometric property of the helix that allows its unlimited growth. Based on the above a concept of a modular tensegrity grid that occurs from the assembly of tensegrity units connected to each other by following a given pattern was chosen. Ease of assembly and simplicity of the connection nodes, typical features of tensegrity grids of the non congruent type, have further suggested their use. Additionally, an objective set from the beginning was to use a single unit configuration, and to keep to the minimum the number of different units required for the construction of the helical structure.

Tensegrity grids of the non congruent type create double layer cable nets held apart by a set of struts. The resulting cable nets can be described as double tessellations, depend on the shape and dimensions of the chosen assembly pattern. These cable nets are similar but not identical and are rotated by an angle of approximately 45 degress with regard to each other; at the same time the rigid members that hold the two layers apart lie on asymptotic lines which explains the geometric complexity in their configuration. Patterns for connecting identical tensegrity units to each other to form spherical configurations have been studied by Hanaor since the late nineties (Hanaor, 1998). The principles, constrains and rules that apply to the geometry of regular single and double curvature configurations (vaults and domes) composed of square base units have also been investigated (Liapi 2001).

In helical tensegrity structures, the helical surface grid construction requires the use of more than one sizes of modules and the development of new principles and rules. A helical double layer tensegrity structure composed of rows of identical units which follow a regular assembly pattern is considered. The conditions and constrains related to this problem and a methodology for the geometric construction of helical tensegrity structures of the non congruent type composed of rows of identical tensegrity units are further investigation and are discussed below.

2. Geometric principles and rules that apply to tensegrity unit dimensions and assembly

Departing from the principles, constrains and rules that apply to the geometry of regular single and double curvature configurations described in earlier publications (Liapi and Kim, 2004), new rules that comply to the helical surface geometry have been developed. Thus in a helical tensegrity structure, which is also a single curvature structure, the upper and the lower bases of adjacent units need to overlap along the radial direction to allow the structure to bend only one way (Figure 1). Unlike to the geometry of a vaulted structure, the sizes of the units in a helical structure along the radial direction need to be reduced proportionally. Therefore, the center points of tensegrity units in addition to being shifted up and down, as is the case with vaulted tensegrity structures, need also to rotate. Figure 2 shows a flat configuration of a 4-unit cluster of a helical structure.

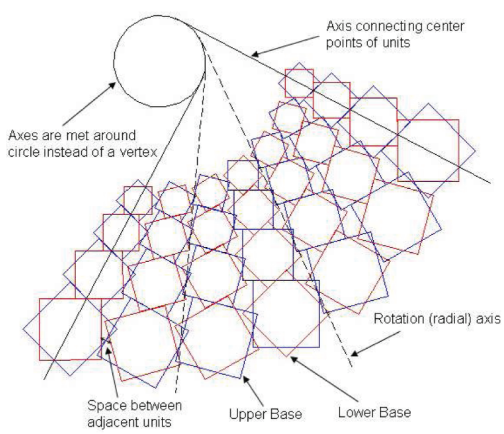

Figure 1: Flat configuration of a double layer helical tensegrity structure composed of square-base units

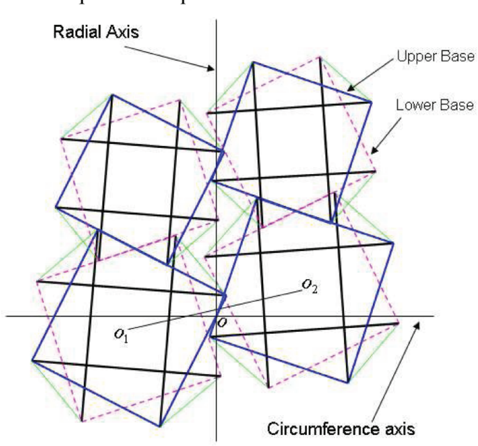

Figure 1: Flat configuration of a 4-unit cluster of a helical structure.

Accordingly the main rules that derive from the conditions/constraints for unit lower base overlap are :

a To generate a helical surface the upper and lower bases of units along the radial direction need to be reduced proportionally

b) In order to create single curvature helical tensegrity structures, the center points between adjacent units across the radial axis must be shifted upwards or downwards, as well as rotated

c) The rotation (radial) axis is not perpendicular to the line connecting two center points o_1, o_2 along the circumferences axis.

d) The line connecting two center points o_1, o_2 does not pass through a mid point o of the overlap because of a rotation of the center points followed by shifting.

e) The amount of upper and lower based overlaps between adjacent units along the radial axis need to be determined.

f) The amount of overlap between adjacent units varies along the circumference axis, due to the proportional reduction.

g) The "gap" between the lower bases should be kept constant along the circumference axis.

3 Geometric Limitations

The amount of overlap between adjacent units as shown in Figure 3 varies from 1 to 0. These extreme configurations apply to both the upper base and the lower base overlap A zero lower overlap configuration is possible when the center line passes through the vertex of the lower base, as shown in Figure 3(a). On the other hand, if the center line passes through the vertex of the upper base, as shown in Figure 3(b), a zero upper based overlap can be created.

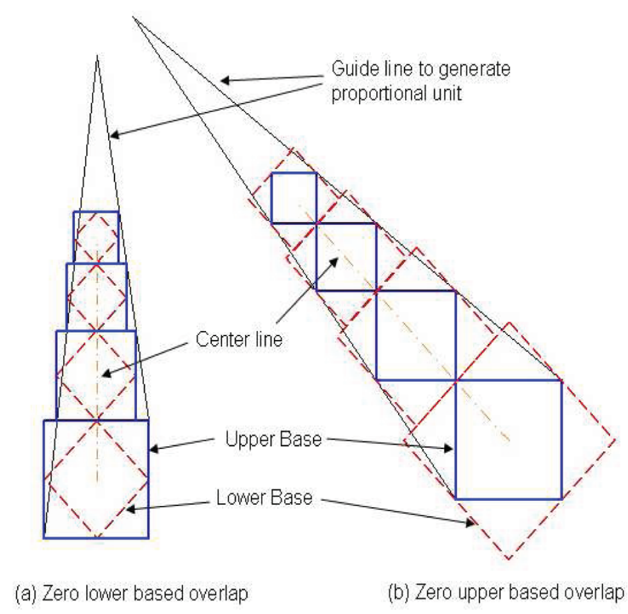

Figure 3: Geometric limitations for the upper and lower base overlaps

4. Geometric construction process

The analysis of the conditions and constrains that need to be followed in order to construct a double layer helical tensegrity structure have led to the development of a step by step method to be followed for the geometric construction of helical A brief description of all the steps in the process follows.

Step 1 Determine the dimensions of the cable bases of consecutive units along the radial axis

The process to be followed for the geometric construction of helical structures starts by determining the dimensions of the cable bases of consecutive units along the radial axis. To ensure proportional decrease in unit sizes, two guide lines with a given angle are drawn. The ratio of reduction in unit size (thus the actual size of individual units) depends on the angle of two guide lines. A high reduction ratio is associated with a wide angle between guide lines, and will cause a high stress to the overlap cables of the upper and lower bases between adjacent units along the circumference axis. The reverse is true for a low reduction ratio. Accordingly, the angle between guide lines needs to be taken into account when determining the sizes of consecutive units.

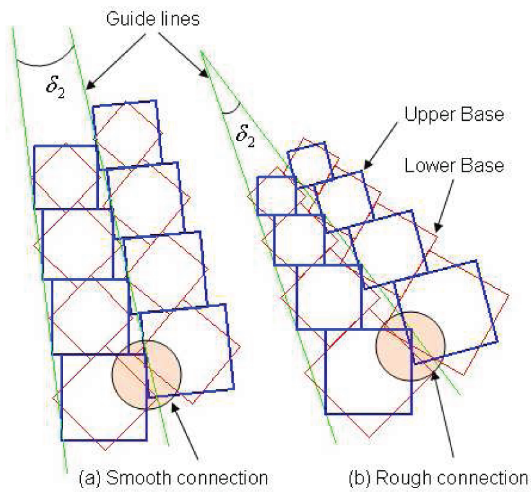

Figure 4 : Configurations of two helical tensegrity unit clusters in which the angle δ_2 between the guide lines assumes two different values

Step 2: Construct a a Tensegrity Column along theRadial Axis

Based on the guide lines, tensegrity units are drawn from the largest to the smallest unit. All upper bases of units are generated before the lower bases since lower bases can be created only after drawing a center line that connects center points between the largest and smallest units. The scheme in Figure 5 shows the geometric configuration of a tensegrity column along the radial axis. Based on the dimensions of the entire structure the p1 that determines the dimension of the largest unitare set and explained. Determining the angle δ_1 plays an important role in this design process since the overlap length of units along the radial axis depends on the value of δ_1.

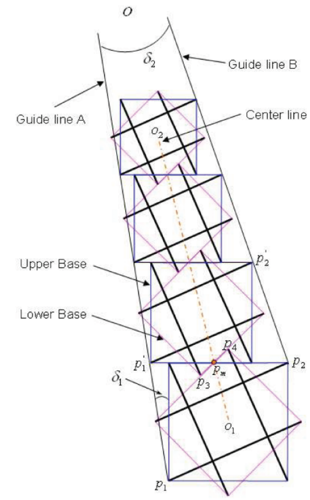

Figure 5 Geometric configuration of a tensegrity column along the radial axis

Step 3 Determine Overlap Conditions

When the first column is generated as described above, another column can be created next to the first with some overlap. At this point, it should be decided whether the overlap between adjacent units will initiate at the largest or the smallest unit. Constrains with regard to the order followed for this process are further set and explained in order to avoid geometric configuration where the smallest unit has a zero overlap.

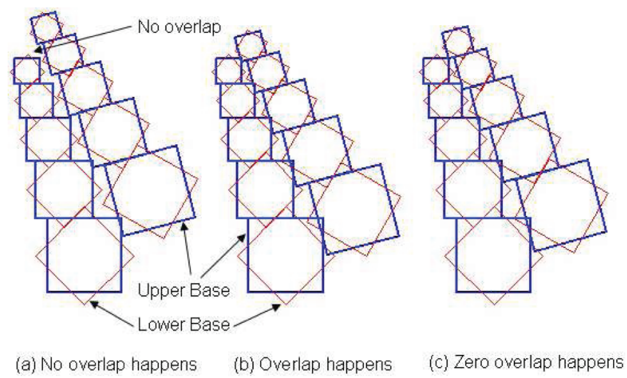

Figure 6: Geometric configurations with different overlap conditions

Step 4 . Construct Identical Gaps within the tessellation

A geometric method for the construction of identical gaps between adlucent units in a clusters of 4 units is presented. Creating identical gaps between adjacent units along the radial direction is most critical to designing a helicoid structure; otherwise the constant rotation angle between units cannot be guaranteed.

- The rotation angle between adjacent units is affected by the unit height.
- The zero overlap configuration theoretically can generate the largest gap.

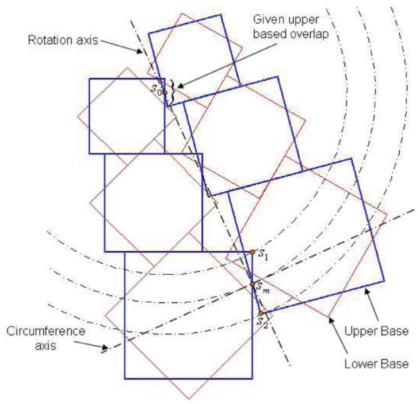

Figure 7 Creating identical gaps

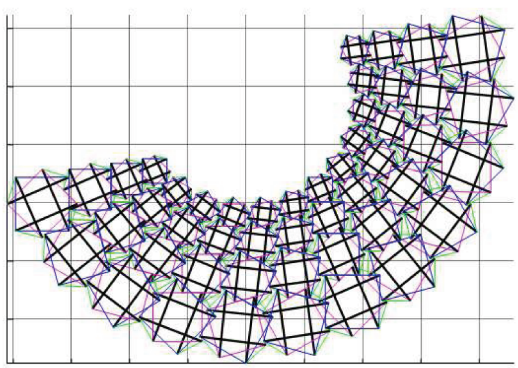

Figure 8 model of a helical tensegrity structure composed of of 4 rows of modules each one composed of 12 identical modules (before module rotation)

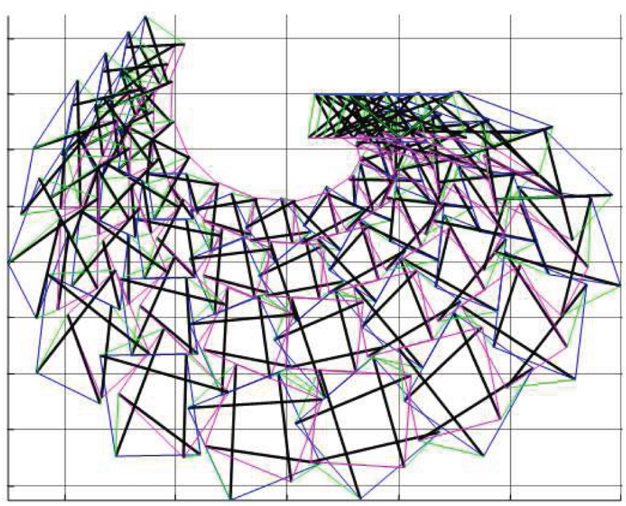

Figure 9 model of the above helical tensegrity structure after module rotation (Top view)

Conclusion

The geometric constrainsts and rules that will make possible the design of double layer helical tensegrity structures of the non-congruent type composed of rows of identical tensegrity modules are set. Based on this the development of algorithms for a parametric description of double layer helical tensegrity structures for the automatic generation of virtual models in a graphical environment has been developed.

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An Anti-Clastic, Double-Curved SLEs Structure

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Abstract

The following case study presents an anticlastic, double-curved foldable SLEs structure designed as translational surface.

Where scissor-like elements (SLEs) are common in mechanical engineering, for example for elevators, they are an exception in architecture. Mostly, this structural idea is used to achieve linear movement. The work of Chuck Hobberman is one of the few examples of studies of SLEs in architectural structures, such as domes.

The investigation SLEs applied to more arbitrary, anticlastic, double-curved surfaces has been, if at all udertaken, neglected. Yet, only if all principle kinds of curvature (elliptic, parabolic, hyperbolic) can be approached by such a construction, it will provide the necessary freedom for contempary design and architecture.

With this paper the feasibility of such a construction will be prooved, a prototype developed. Its geometrical as well as its structural implications will be investigated.

Keywords: architecture, scisor-like elements, deployables, adaptable construction

1 Introduction - basic structural units and deployability conditions

In a scissor mechanism, often called a pantograph, duplet, X-unit or Scissor-Like-Element (SLE), each rod has three pivot joints: one on each end and one toward the middle. The basic structural unit consists of two such rods connected at the intermediate point and hinged at the four end points to end nodes of other SLEs. The structure shows an internal mechanism: a single axis of rotation. Shortening one spatial direction (e.g. vertically) of the pantograph results in the lengthening of the other spatial direction (e.g. horizontally).

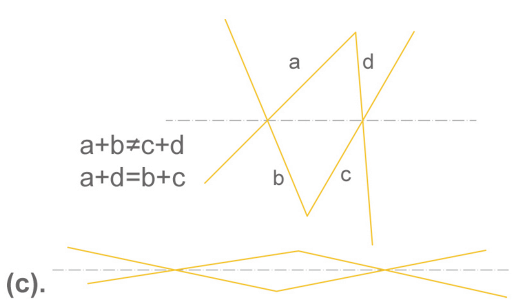

Figure 1: deployability conditions

The mechanism can be folded about both horizontal and vertical axis. Irregular patterns [Escrig and Valcarcel, 1993] or SLEs units capable to form a curved two-dimensional structure lack one or both of these properties. Foldability is only possible if further restrictions are taken into account. Compatibility conditions between the lengths of each strut of the whole have to be met. Figure 1 shows the relationship between the lengths of the SLEs for a folding about horizontal axis.

"If we connect the basic SLEs patterns between them, in such a way that the compatibility of the movement of each piece is guaranteed, we obtain a complex system able to grow in one, two or three spatial directions, building a complex assembly with the same properties as the elements: expanding and folding abilities." [Escrig and Valcarcel, 1993, p.71] A three-dimensional flat structure made of square deployable units is a simple design task. Figure 2 shows a development of inner and outer SLEs on a common plane and the geometric relationships between the lengths of the bars. The outer SLEs defining the polygons are regular. Similar conditions like Figure 1 (a) should be satisfied for the bracing diagonals.

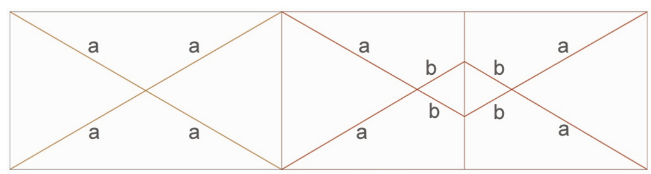

Figure 2: outer and inner SLEs

Figure 3 presents a model of deployable flat slab made of 10x5 square units.

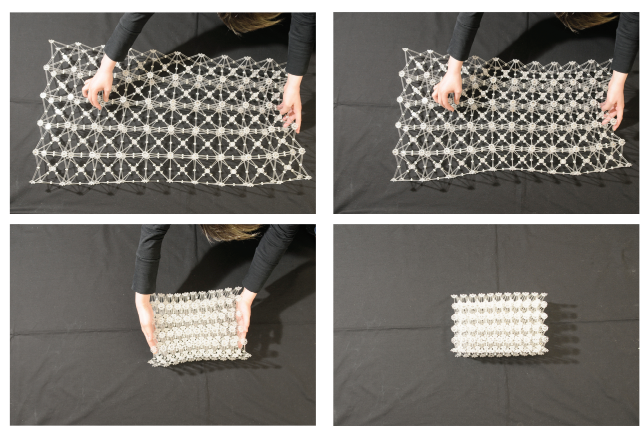

Figure 3: deployable flat slab

Not only a square but also any regular polygons can be the basis of the single units that make the structure. The inner angle between the diagonals β is then given by: β=360°/n. n being the number of sides of the polygon.
It will be shown in the following study that it is possible to build a two-dimensional SLEs structure of any shape. This can be

extended to a single-curved structure. As a consequence there is no limit for cylindrical shapes building the basis for foldable X-frames. The deployability constraints are the same as for curved two-dimensional structures. Designing the SLEs for the bracing diagonals is one of the difficulties, which occur, when detailing such a structure.
To build a double-curved three-dimensional structure of SLEs units, is far more challenging and in some cases can be impossible.

A number of concepts of dome-like pantographic structures are proposed by many researchers in the field. In general, the main characteristic of dome-like structures is that lines connected upper to corresponding lower nodes go through a common point S instead of being parallel as in a flat structure [Gantes at al. 1993]. The basic three-dimensional unit is in this case a truncated pyramid.

In a double-curved structure different from a dome the lines cannot go through one single point. Another methodology has to be found, that can satisfy the deployability conditions. In a general case of an arbitrary unit like the one in Figure 4 these are a+b=c+d, d'+c'=e+f, e'+f'=g'+h' and h+g=a'+b'.

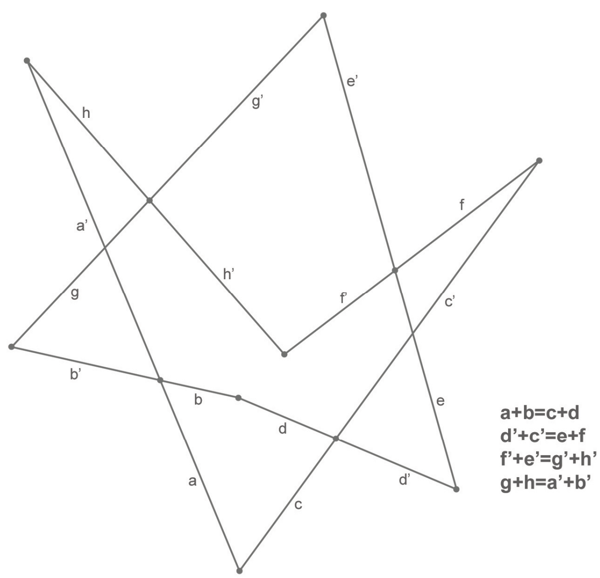

Figure 4: unit of an arbitrary double-curved SLEs structure

Similar conditions must be satisfied when several units are linked together.
A structure made of SLEs can fold only if the sum of the length between the pivot and one of the end hinges of one bar and the length between the same pivot and corresponding end hinge of the second bar, building together a pantograph, must be the same for all pantographs linked together in the same nodes.
Due to these compatibility restrictions most of the realized and even recently investigated full size scissor-like structures and prototypes are limited to some regular geometric shapes in its deployed configurations, either flat or dome-like. The manifold of other geometrical shapes are under-represented and therefore are the subject of this study.

2 Geometrical Concepts for a curved SLEs Mechanism

Using the properties of an ellipse we can construct a pair of SLEs in a pre-determined configuration with intermediate pivots on an ellipse. The resulting structure will ever fold properly (Figure 5).

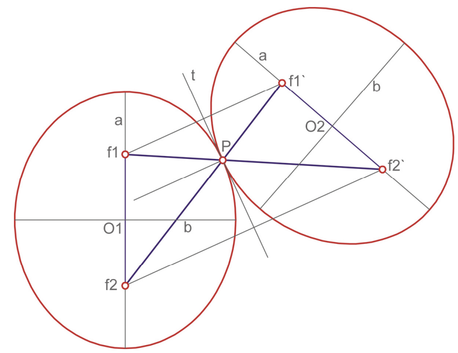

Figure 5: elliptical properties of a SLEs unit

The ellipse is then the generated meridian of a prolate rotational ellipsoid. Every meridian curve of the ellipsoid is a basis of a SLE unit. In this way we can connect pantographic units in two or more spatial directions with proper mechanical properties.

The rolling of two ellipses can also be described as true elliptical gears. They can only be made to mesh properly if they are twins, and if they are rotated about their focal points [Chironis and Sclater, 2001, p.267]. If we link more such ellipses together we get a chain of elliptical gears, the rotation of each of them about the own focus can be controlled separately. The result is a two-dimensional SLEs structure. Its shape and curvature can be set arbitrary (Figure 6).

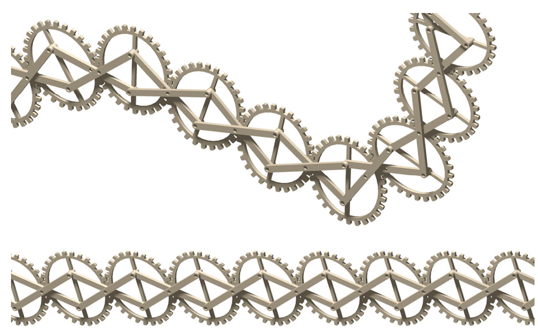

Figure 6: chain of elliptical gears, any 2D curve can be subdivided in this way and will be foldable

In every instant each ellipse is symmetrical to its neighbors about a tangent through a corresponding mutual Point P [Glaeser, 2007, p.300]. The lines connecting the foci of these ellipses f_1, f_1\`, f_2, f_2´ are building an antiparallelogramm (Figure 5). The long sides crossing in point P are the bars of a SLE unit. The other two $f_1 f_1$´ and $f_2 f_2$´are the normals of two plane parallel curves, one going through the upper foci of the ellipses and one through the corresponding lower foci. The curves describe the shape of an arbitrary two-dimensional pantographic structure.

Given the fact that the elliptical gears are connected in both of their foci, the intermediate point P is not just cycling the ellipses but also shifts along the lengths of the connected lines. As a consequence of this method we can also make a structure that not just folds but also can change shape. This can be obtained by introducing an internal mechanism and let the middle connection point of the bars slide.

Combining such two-dimensional curved sections with a sequence of regular SLEs, a three-dimensional single curved structure of arbitrary form and changing shape is generated.

A limitation of the concept of chains of elliptical gears can be found in the fact that symmetry exist only between two neighboring ellipses (about a common point P). There is no relationship to the other subsystems of the chain. This becomes a tangible problem when applied in three-dimensional space. A methode for subdividing an arbitrary surface using its normals as a basis for a scissors structure could not be found. In fact, it seems to be impossible to design a single unit with lines connecting upper and corresponding lower nodes that do not intersect in a point or in a line. As a consequence, this paper focused on studying how to design a structure in which the major axes of the ellipses are kept parallel while the shape of the frame remains arbitrary.

Assuming that the ellipses underlying the structure are congruent with the same linear eccentricities and the major axes should be parallel. Hence the polygon with vertices the focal points of two such ellipses can be only a rhomb or a rectangle as a special case. Rectangular units can generate only a flat configuration.

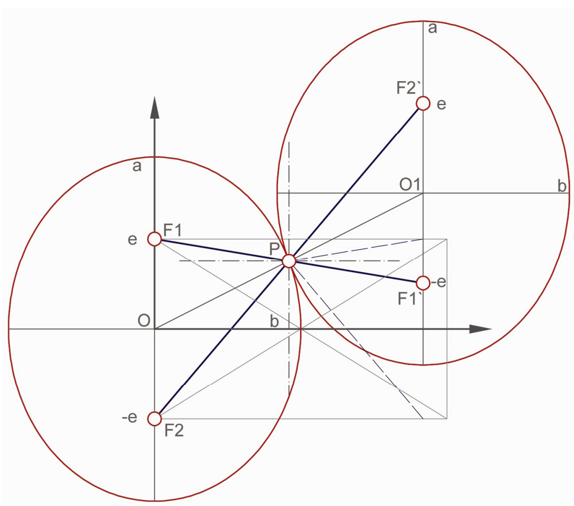

Figure 7: concept for a double-curved SLEs structure

The ellipse k in Figure 7 has a center O the middle point of a side of a square. The corresponding vertices are the foci of the ellipse F_1 and F_2. The minor axis is the distance between point O and intersection point of the two diagonals of the square. The length of the major axis equals in this case the length of a half diagonal. Point P is any point of the ellipse and the distances between P and the foci are half of a pantograph. A local Cartesian coordinate system is introduced at P. If we reflect the segments PF_1 and PF_2 about the two coordinate axes or we apply a single rotation about P with rotational angle of 180° [Pottmann at al. 2007, p.146] the image is the second part of the pantograph. The image points $F_1´$and $F_2´$ are the foci of an ellipse congruent to first one. The points F_1, F_2, $F_1´$and $F_2´$are the vertices of a rhomb with two sides parallel to the vertical axis. When we repeat the transformation with an arbitrary point P on the second ellipse and so on, the result is a two-dimensional frame of rhombs with every two sides having the same length and parallel to a global vertical axis. The length of the other two sides varies for every polygon in relation to the instant position of point P.

The coordinates of the point P can be expressed as functions of the angle φ between the line from O trough P and an x axis of a coordinate system in O (parameter equations of an ellipse). The coordinates of any point P of the ellipse in the case of Figure 7 are P (bcosφ, asinφ). a and b being the semi major and semi minor axes of the ellipse. They are known trough architectural requirements and are the same for all ellipses of the frame. The distance between the two centers of the ellipses is the double distance between O and P.

By varying the angle φ we have a family of rhombic units that can be linked together in an arbitrary way, always suited for a SLEs structure. Rearranging the rhombic units yields a different polygon curve. The polygon curve is a discretization of a smut curve and the vertices of the polygon are points of this curve.

3 Design of a SLEs Structure Approximating Second Order Surfaces

To keep the connection of upper to corresponding lower nodes parallel to a global vertical axis, will be also the concept for the the double-curved SLEs structre investigated in this paper. Thus, the surface describing the shape of the structure, its inner and outer skin, will be simply translated along this axis. The structure has two identical layers and their projections on a horizontal plane overlap.

It has been shown that to build a curved configuration with the above assumptions, the polygons of a single SLE unit must be rhombs. Connecting four such plane patterns in two spatial directions a three-dimensional single unit or a prism is obtained with every two sides being parallel. The upper and lower sides of the prism are also planar rhombic polygons. To use such units as a frame for SLEs structure is a powerful tool for designing some special surfaces but also the main restriction for generalizing this method

The prismatic SLE unit can be regarded as part of a pair of discretized planar curves, generating a translational surface. When the planes of these curves are orthogonal, a family of translational surfaces is generated which can be easily approximated by SLEs. This can be done by using the method described in the forgoing Chapter. Figure 3.26 shows such a structure. The result is a discrete surface with planar rhombic faces. The projections of these polygons on a horizontal plane are rectangles. The case study demonstrated in the following chapter is based on this assumption.

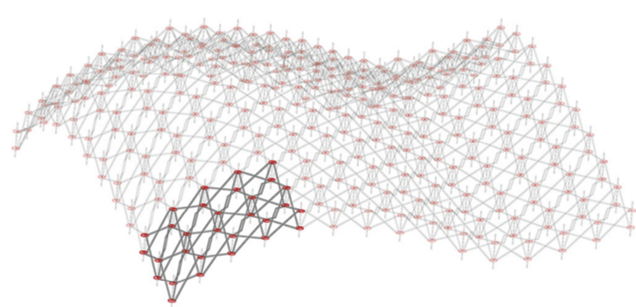

Figure 8: SLEs structure approximating a translational surface

It is possible to construct also other then orthogonal configurations. However, this will not lead to a greater formal variety, yet it will lead to problematic joint details, resulting in even bigger knots.

Due to the fact that pantographic units in three-dimensional structures are hinged together in two or more spatial directions at the same nodes the generatrix of the surface should be also parallel. In a ruled surface the straight lines, called generators of rulings [Pottmann et al., 2007, p.311], lay, in general, not in parallel planes. Therefore we cannot subdivide an arbitrary ruled surface using rhombic planar polygons and meet the geometrical constraints for scissors structure. This was proofed by trying to create a SLEs structure shaped as hyperbolic paraboloid as double ruled surface. Instead of rhombic polygons, trapezoidal polygons should be the faces of a discrete ruled surface.

A method for design a flat structure of trapezoidal units is presented by Gantes and coauthors [Gantes et al., 1993]. It should be possible to modify this method and create a double ruled surface.

4 Case Study

For the case study, first a parametric model has been developed. This first model did not consider physical properties, such as bar or rod thicknesses or the size of joints, but showed that the structure folds and deploys smoothly, prooving the first considerations to be correct. The same model was then modified implementing joints of discrete size, simplified as circles. Thus, to a certain extent, also excentricity in the connecting joints could be taken into account.

Furher an acrylic model of scale 1:20 with joint diameter of 150mm and bars of thickness 1,5mm was built. In this model the excentricity problem was ignored. Yet, it worked properly, due to material deformation. Upper and corresponding lower joint hubs were given the same design.

To test the mechanical properties of the construction and to avoid mistakes due to the small scale model, a kinematic simulation with CATIA V5 12 (DMU Kinematics) was established. The eccentricity of scissor pairs was considered and the elements are of realistic, yet, not calculated dimensions.

As expected, the same structure tested with a small scale model did not work as a mechanism without allowing a material deformation and is over constrained. Thus, the kinematic model was modified and some requirements for the structure had to be defined.
The structure should retain the single degree of freedom of a basic SLEs unit. It should be capable of being deployed or folded without inducing strain in any of the structural components. The frame should be stress-free without bending members in all configurations as a bearing structure. It should be a mechanism that can work as a structure by means of proper mechanical devices to fix it at a desired position without additional elements.

To comply with these demands an additional rotation about the central axes of the joining hubs for all inner rods was inserted. This provides an additional, yet, limited degree of freedom, since upon deployment the angles between inner and outer SLEs need to diverse slightly from the initial angles. This requires also a little change in the lengths of inner bars, yet, proportionally. This is achieved by introducting sliding connections in the central nodes. The perpendicular angles between the outer SLEs in a projection on a horizontal plane remain constant. The resulting construction is a mechanism with a single degree of freedom, a single rotation.

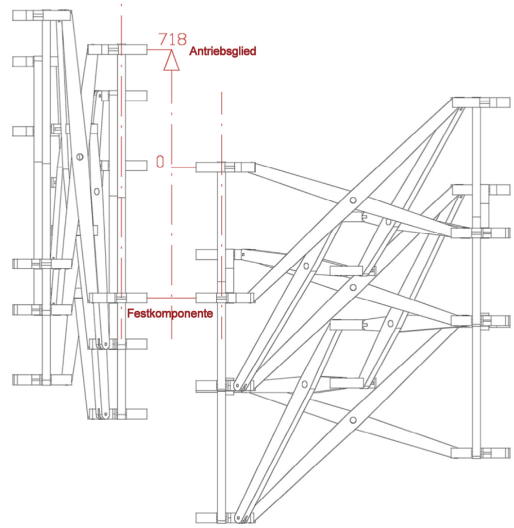

Figure 9: illustration of the actually investigated mehanism

Instead of controlling this rotational degree of freedom we can alter one of the heights of the structure to control the movement of the construction. In the DMU model the distance between the centers of one upper and the corresponding lower hubs is used as kinematic order (Figure 9). This allows multiplying the three-dimensional units without changing the command.

In an actually built structure it will be better to use the horizontal distances between the lower hubs of the first and last SLEs units in the both spatial directions. In this case, the structure can be deployed and folded for example with the use of a gear rack and a pinion. The runway girders of the driving units can then work as tie-rods and contribute to the load bearing capacity of the structure.

Conclusion

The prototype structure was investigated geometrically, as a physical model and finally by a kinematic simulation.

SLEs applied to more arbitrary, anticlastic, double-curved surfaces thus have been proved feasible. Structures like this could combine well-known mechanical mechanisms with the challenge of an innovative, adaptable design approach.

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Design and Panelization of Architectural Freeform-Surfaces by Planar Quadrilateral Meshes

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Abstract

The implementation of freeform shapes in architecture is an area which encompasses great challenges in engineering as well as novel design ideas, and which consequently has high public exposure. However, the geometric basics of realizing double curved surfaces as e.g. steel/glass constructions with planar faces remained largely unexplored. Planar quadrilateral faces and true freeform geometries seemed mutually exclusive. Only recently the high potential of optimized mesh geometries has been realized. The aim of our present research is the computation and interactive design of planar quadrilateral meshes (referenced as PQ meshes) with specific properties relevant for design, construction and production processes in the field of architecture.

PQ Meshes are not only capable of realizing the entire spectrum of freeform shapes, but at the same time provide the basis for a multi-layer support and cladding structure with planar faces and optimized joints.

Keywords: Architecture, Architectural Geometry, Planar Quadrilateral Meshes, PQ meshes, Subdivision, Freeform Surfaces, Freeform Design, Panelization

1 Introduction / Motivation

Architects are confronted with many design tools for CAGD that have increased the possibilities in freeform geometry modeling using e.g. NURBS or subdivision. Virtual representations of complex architectural spatial models in images and films became vital for the architect's core business.

The general use of CAD has accelerated the pace of the overall architectural design process. Even though CAD systems have kept up with the development of CAGD methods, CAD tools still do not offer adequate solutions for linking architectural freeform design to the process of manufacturing and construction. The question arises how to efficiently break down complex geometry from different sources. Proper implementations of architectural constraints within the context of design tools are still unsatisfactory.

PQ meshes offer new possibilities for planar faces, special offset properties, on mesh parallelism and on subdivision methods for interactive design. Architectural and geometric advantages of general PQ meshes have been widely discussed in [Pottmann et al 2006] and [Brell-Cokcan, Pottmann 2006].

In this paper we will show our recent results and advanced methods in PQ design of complex freeform building envelopes considering crucial manufacturing and architectural constraints.

1.1. Quads vs. Triangles

The easiest way of segmenting and "planarizing" a double curved surface is to lay out a mesh of triangles. This technique can be seen at recent projects such as the glass roof of *Frankfurt Hoch 4* by Massimiliano Fuksas. As opposed to triangular meshes, PQ meshes have the advantage of more lightweight connections of joining members along with a reduced need for cladding elements. From the architectural point of view, PQ meshes appear less dense and in general motivate the form aesthetically.

1.2. Basic PQ-Design

Quadrilateral meshes are usually non-planar. To generate PQ meshes, specific methods have to be used. One of them can be seen in certain projects of Schlaich Bergermann, where affine geometric operations are used to generate special classes of exact PQ meshes [Glymph et al. 2006].

Another well known example is the *Sage* by Norman Foster (Fig.1), segmented by flat, rectangular panels of glass. As impressive as this structure may seem, it has been obtained by using rather simple geometric operations, which are inappropriate for the design of arbitrary free-form shapes [Schmiedhofer 2007].

Additionally, a simple strategy is to mix planar quads and triangles in areas where two triangles can be combined to flat quadrilateral faces. A prominent example for that is the freeform shell of the *Milan Trade Fair* by Massimiliano Fuksas, a rather complex looking shape generally segmented into triangles, where neighbouring coplanar triangles have been merged into planar quadrilaterals.

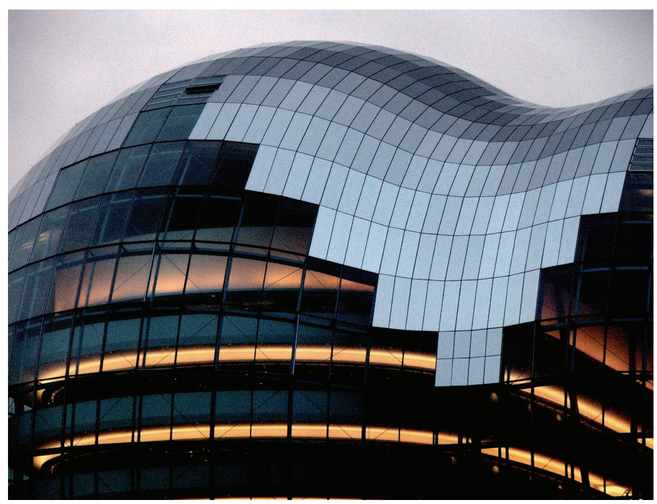


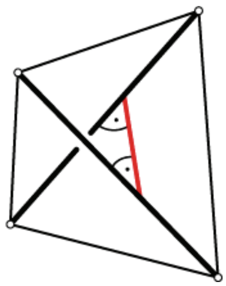
Figure 1: PQ-design by simple geometric operations: The *Sage* by Norman Foster.

2 Methods / References

PQ meshes and their geometric properties have recently been addressed in [Liu et al. 2006]. While the close connection of PQ meshes to so-called conjugate curve networks on a surface have been shown much earlier [Sauer 1970], the authors propose approaches for the layout as well as for approximation of freeform surfaces with non-trivial PQ meshes. In this paper we present further development of these approaches and their application in architecture.

2.1. Planarization

The authors of [Liu et al. 2006] use a non-linear optimization to perturb the vertex positions of a quad mesh. The goal is to let faces become planar while keeping a fair shape and, as an option, closeness to a reference surface. The following improvements have been made to this optimization framework in order to improve the applicability to architecture:



Measure of planarity. We employ the diagonal distance of quads, which improves convergence compared to the measures presented in [Liu et al. 2006]. Furthermore it is more closely related to material properties.

Architectural constraints. From facade construction and design intent points of view it makes sense to constrain vertices to certain planes, e.g. defined by floor slabs (Fig.2) or symmetry planes. We have incorporated this into our optimization framework.

System lines. Polygons defined by corresponding edges of a quad mesh can be realized with different visual impact on the overall facade structure. We account for that by accordingly weighting the fairness of these polygons in the optimization.

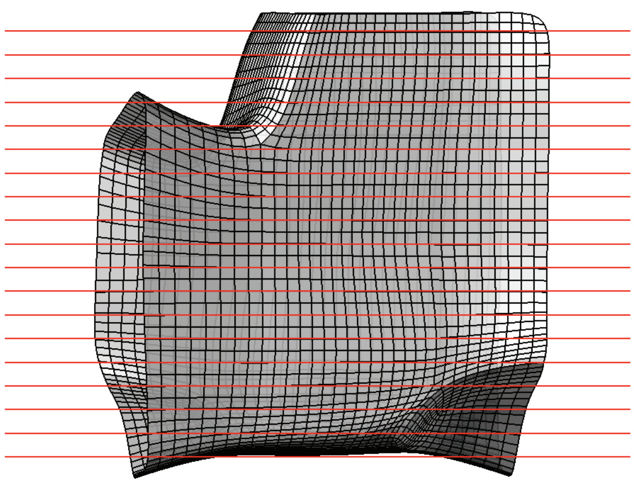


Figure 2: Floor slabs to be matched (red) as an example for architectural constraints on a PQ mesh.

A crucial input for planarization is an initial quad mesh already close to planarity. The following section elaborates on strategies for using this optimization framework within the context of architectural applications.

3 Advanced Design-Strategies for PQ Meshes

3.1. Interactive Design

Starting from scratch, this design approach results in a PQ mesh-design via subdivision modeling followed by subsequent steps of planarization and subdivision of a coarse initial quad mesh.

The designer first creates a very simple coarse quad mesh approximating the shape he wants to achieve, e.g. a box. We will refer to this as the *initial mesh* throughout this text. Then, he edits it according to his likes while simultaneously having an eye on the subdivided result of his initial mesh (Fig.3). This can be done in the most common CAD-design-tools. Note that this 'subdivision-preview' is used to only help estimate the shape of the planar result and does not guarantee planarity. The more planar the quads of the initial mesh are, the more likely the planar result will appropriately resemble the subdivision preview later on.

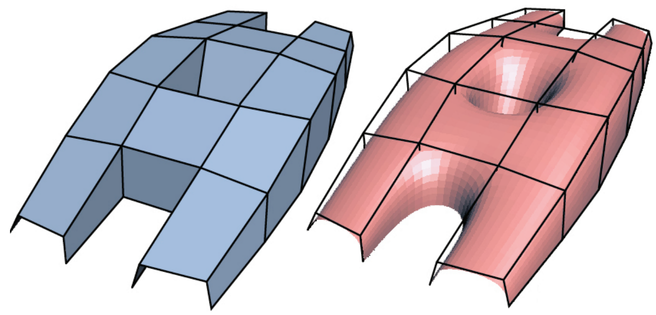


Figure 3: Initial mesh (left) and initial mesh with (non-planar) subdivision preview.

After this design-phase, the initial mesh is subdivided and planarized in subsequent steps: Subdivision destroys the planarity of quads, afterwards planarization perturbs mesh vertices on a global scope such that quads become planar again. Subdivision refines this planar mesh but again destroys planarity, and so on. This procedure is repeatedly applied until the desired degree of planarity and refinement is reached. The latter naturally depends on the intended size of panels. Optionally, this process can be extended to not only optimize for planarity, but also for closeness of the mesh to a reference surface. Thus, by using the subdivided initial mesh as a reference, it is easier to make the planar result resemble the look of the subdivision preview at design-time.

The number of quads in the subdivided mesh depends on the used subdivision-algorithm. Although for our needs we use Catmull-Clark subdivision, the algorithm used doesn't matter much as long as it is a quad mesh subdivision method. Note that it is even possible to manually insert new system lines where needed, thus controlling the number of resulting panels.

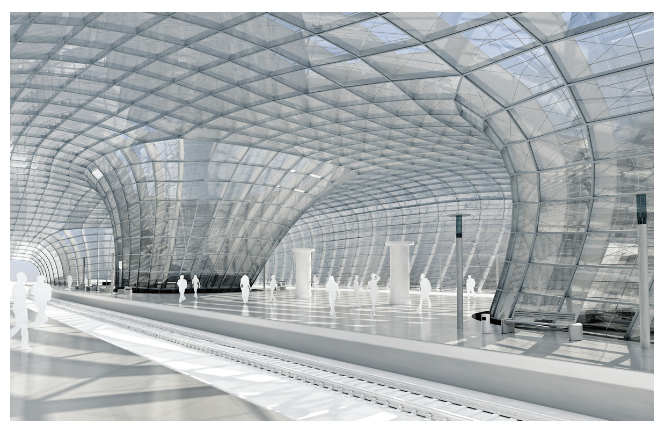


Figure 4: Architectural PQ Design created by the interactive approach of section 3.1, resulting from the initial mesh in Fig. 3.

3.2. Surface Remodeling

Here, we aim for a PQ-mesh approximating a predefined freeform surface. We will demonstrate two possible approaches at hand of a recent architectural project - 'The Opus', an office building for Abu Dhabi by Zaha Hadid Architects, featuring a complex freeform facade.

3.2.1. Manual Surface Remodeling

The manual remodeling approach tries to match the given surface best by means of the interactive design procedure mentioned before. Additionally, the given freeform-surface will be used as a reference in subdivision modeling (Fig 5). An appropriate coarse representation has to be created manually, by laying out an initial mesh resembling the given surface and editing its vertices such that the subdivided mesh will approximate it as good as possible. The similarity between the given surface and the subdivided initial mesh depends on the initial mesh's connectivity as well as on its resolution.

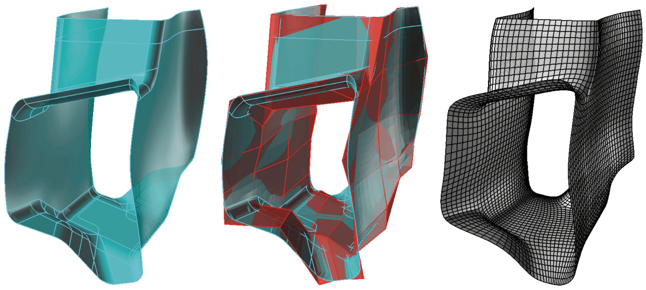


Figure 5: Manual Surface Remodeling. An initial mesh (middle, red) is manually matched to a freeform reference (left). Right: the subdivided planar result.

Afterwards, the initial mesh subsequently gets subdivided and planarized. Interactive editing of resulting new vertices between these steps is a way to match the surface more exactly on one hand, while on the other constraints such as panels which have to be flush with floor slabs can be met accordingly.

3.2.2. Subdivision Fitting - Automatic Surface Remodeling

Manual surface remodeling has a major drawback: There are infinitely many possibilities to choose the coarse initial mesh. We have partially been addressing this problem by employing so-called 'Subdivision Fitting'. Given an initial mesh with rough vertex positions, we use an optimization procedure to compute specific vertex positions, such that the subdivided mesh will be close to the reference surface and the quads become nearly planar. The use of subdivision helps in obtaining a smooth result, nevertheless we use fairness as an optional goal for this optimization.

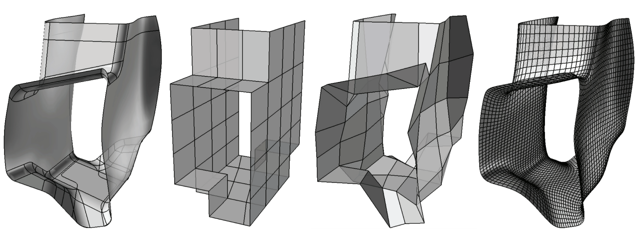


Figure 6: Subdivision fitting. A manually layed out rough initial mesh (second from left) is automatically matched to a freeform reference (left). Second from right: the resulting initial mesh for refinement, right: the subdivided planar result.

Hence, an appropriate initial mesh featuring meaningful connectivity and carefully chosen singular points has to be layed out manually, without caring too much about the positions of its vertices. After that, subdivision-fitting will automatically match it to the given reference-surface. The result will be a coarse initial mesh which - after a predefined number of subdivision steps - will resemble the given freeform surface as good as possible.

Yet, one major limitation of this method is the possible large variation in size of the resulting planar quads. The optimization naturally tends to populate regions of higher curvature with more initial vertices. This biases equal distribution of quads, resulting in unequally sized panels which are in most cases unwanted for architectural applications. This circumstance can to a certain extent be controlled by considering the original surface's curvature when designing the initial mesh: Granting more detail to highly curved regions in the initial mesh will help distribute structure-lines more evenly. However, depending on the connectivity of the quad mesh, this could also introduce undesirable detail in other regions.

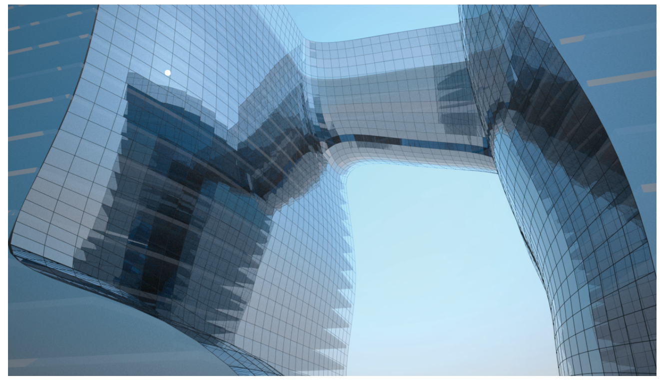


Figure 7: Rendered result of planarizing 'the Opus' - facade.

3.3. Surface Approximation

The close connection between conjugate curve networks on a smooth surface and PQ meshes leads to a promising approach for the approximation of freeform surfaces. In this case we (1) analyze the curvature flow of the given reference surface, (2) lay out a conjugate curve network on it and (3) extract a quad-dominant mesh resembling the conjugate curve network. Such meshes will be close to planarity and thus suitable for planarization [Sauer 1970]. Step 1 can be carried out using well known methods. Little work has been done to exploit the degrees of freedom for step 2 [Schiftner 2007]. Recent results on surface parameterization may be adapted to solve step 3 [Kaelberer et al. 2007]. Figure 8 shows an approximation of a complicated surface. Obviously, work remains to be done in order to make this approach suitable for architectural applications. The challenging task is to lay out a highly regular quad mesh which picks a suitable amount of detail of the reference surface.

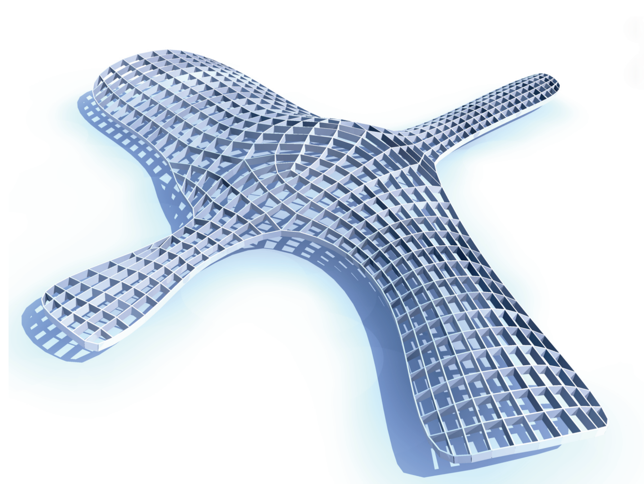


Figure 8: Panelization by surface approximation.

4 Conclusions and Future Research

Figure 9 shows an overview of the design strategies presented throughout this paper.

Limitations of the presented approaches point out topics that need further investigation. An important part is to fully automate the creation of initial quad meshes for remodeling with PQ meshes. This needs a thorough understanding of conjugate curve networks on freeform surfaces on a global scale. Existing ideas include the use of a shape database which could be used to assemble an initial mesh using a decomposition of the freeform surface into known patches. Moreover, surface parametrization methods like [Kaelberer 2007] could be used. Subdivision fitting inherently lacks degrees of freedom given common architectural constraints like equally sized panels. Therefore, it is feasible to explore multiscale approaches for remodeling. As already mentioned, the layout of conjugate curve networks on freeform surfaces is an important part of approximation with PQ meshes, which has not yet been satisfactorily solved.

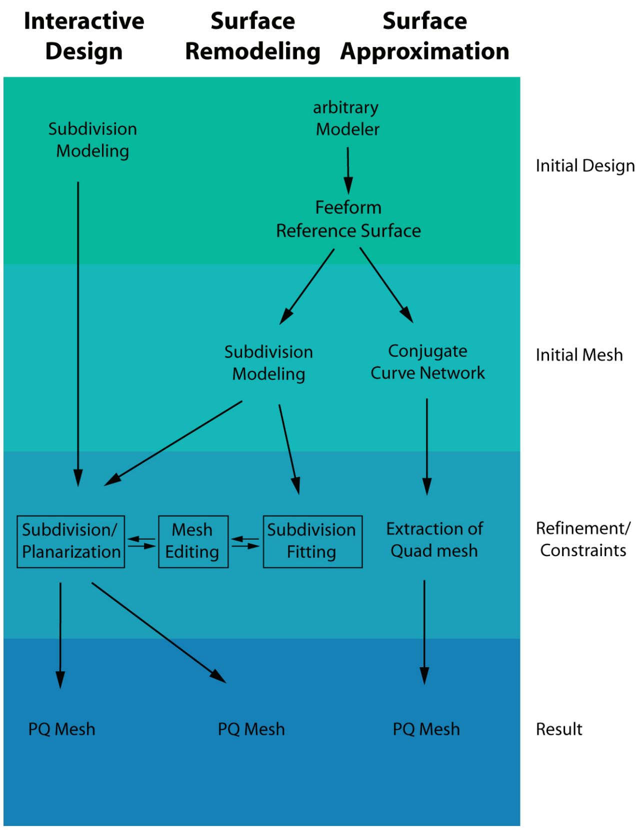


Figure 9: Overview of PQ design strategies presented in this paper.

Acknowledgements

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Beyond Isocurves

Dipl.-Ing. Hanno Stehling
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Abstract

The project "beyond isocurves" deals with the distribution of point grids on trimmed NURBS surfaces, the creation of three-dimensional module grids on stacks of such surfaces and an approach of script-driven structural dimensioning.

"Beyond Isocurves" is a student project done at the University of Kassel, departement of structure (Prof. Manfred Grohmann). Tutors were Dipl-Ing. Oliver Tessmann and Dipl.-Des. Markus Schein.

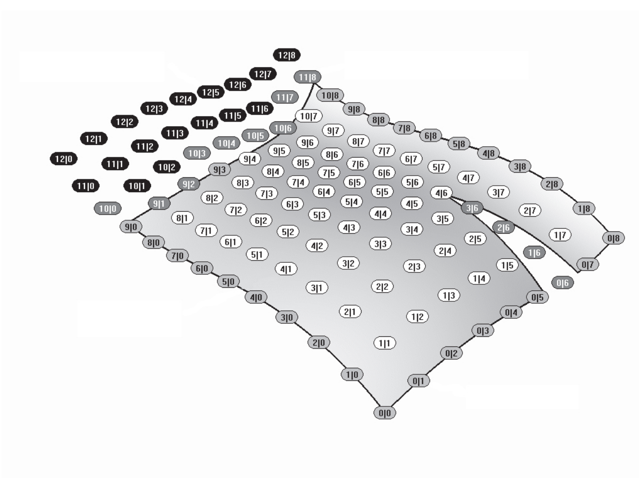
Keywords: trimmed NURBS surfaces, surface relaxation, RhinoScript, modular geometry

1 Point grids on trimmed NURBS surfaces

A popular way to create three-dimensional structures following a given surface is to populate the surface with parametric modules using the surface's u/v coordinate system.

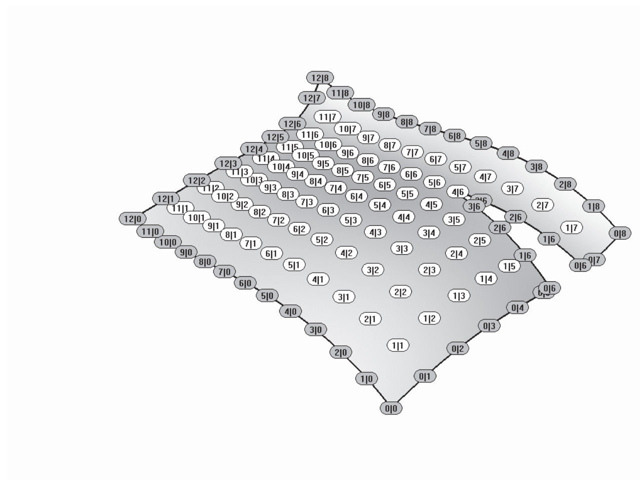
This method is fairly simple as long as the surface is an untrimmed NURBS surface. However, trimming does not affect a surface's u/v parameterization, so if the same method is applied to a trimmed surface, the points will still resemble the surface's untrimmed version.

To create a point grid resembling a trimmed surface, an iterative process is applied, with the "untrimmed grid" as starting point: It is possible to detect, if a point lies on the trimmed surface or in one of the cut off regions. Thus it is also possible to identify the points neighboring the trimmed surface.



In a first step, those points are pushed onto the surface. Secondly, a process of dynamic relaxation is run, where every point on the surface tries to be the area centroid of the quadrangle described by its surrounding points. After these two steps, the process proceeds to the next iteration, so that in the end all points are lying on the trimmed surface.

Finally, some points need to be doubled: If there is a gap in the surface between two adjacent points, one of the points needs to have two instances, one on each side of the gap. Only by applying this rule the final grid will have "cuts" where the surface is trimmed. Otherwise such gaps would simply be spanned by later applied geometric modules, being represented only by a slight anomaly in the grid.

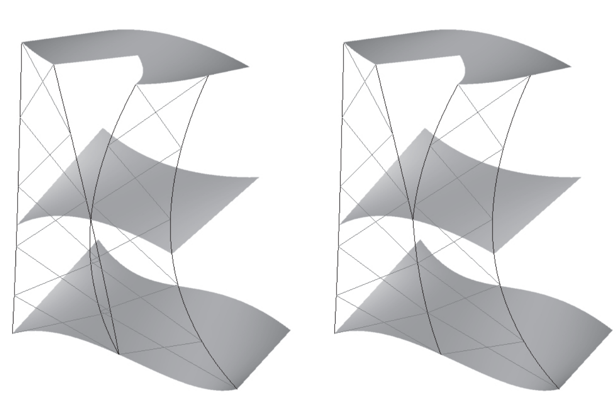


2 Three-dimensional grids on stacks of trimmed NURBS surfaces

A row of surfaces populated with equally-sized point grids can be regarded as a stack, from which a third dimension can be built by connecting the corresponding points on each surface.

But unlike the first two dimensions, the grid's precision is predetermined – the numer of points equals the number of surfaces.

This issue can be solved by connecting the corresponding surface points through interpolated curves and placing an arbitrary number of points along them using the t parameters.



Another problem arises if some of the surfaces have points with multiple instances (due to trimmed gaps, see 1). These multiple points cause the interpolated curves to overlap, leading to deviations between points that should be common.

This issue is solved by segmenting the curves into parts with common points and parts with deviating points. This way the possibility of gaps in point grids is brought into the third dimension.

3 Rhino-RSTAB-Interface for script-driven structural dimensioning

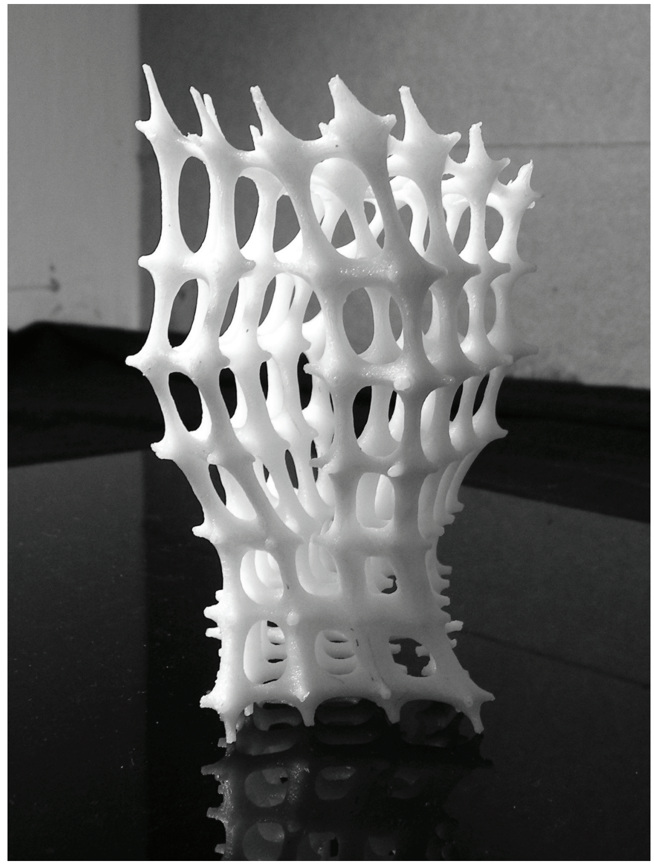
During the project a scripting interface between Rhino and the structural analysis application RSTAB was developed. With this interface it is possible to calculate node representations of a structure within RhinoScript environment, so that the results can be used for creation of the final geometry.

4 Proof of concept: a 3d-printed test object

For the end of term exhibition at the University of Kassel an object consisting of 4x4x7 instances of a simple starlike module running over a stack of six partly trimmed surfaces was created.

The radii of the module connections were constrained by the forces applied to the respective grid members.

The final script was a complete generator containing all steps from surface population to meshing, including the above explained techniques. The object could be printed without any manual editing.



Iterative Geometric Design for Architecture

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IBOIS - EPFL

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Abstract

This interdisciplinary research project presents a corporation of architects, mathematicians and computer scientists. The team researches new methods for the efficient realization of complex architectural shapes. The aim is to develop computer-aided solutions which optimize the design and production of free-form surfaces. Therefore, the team worked out a new surface method. The method studied provides new form-finding possibilities while satisfying a certain number of material and construction constraints.

Keywords: architecture, applied discrete geometry, IFS, timber construction

1 Introduction

In order to present the surface method studied, some mathematical background needs to be explained. We consciously try to discuss the mathematical bases without using formulas and try to explain the method studied by graphical illustrations. The relation between the mathematical method of geometric surface design and the physically constructed building will be shown by examples in the second part of this presentation.

2 Mathematical Background

2.1. Of monster Curves ...

The Cantor set, also called Cantor dust, is named after the German mathematician Georg Cantor [Cantor 1884]. It describes a set of points which lies on a straight line. In the end of the 19th century, this figure attracted the attention of mathematicians because of its apparently contradictory properties. Cantor himself described it as a perfect set, which is nowhere dense. Further properties, such as self-similarity, compactness and discontinuity, have been studied years later.

The geometrical construction of the Cantor set can be explained as follows: Take a straight line segment, divide it into three parts of equal length and remove its middle third; divide again each of the resulting line segments and keep removing their middle thirds. If you repeat this for each of the new line segments, you will end up with the Cantor set.

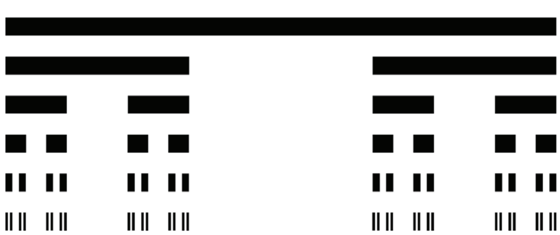

Figure 1: Cantor Set

The Von Koch curve belongs among the first found and best known fractal objects. In 1904, the Swedish mathematician Helge Von Koch described it for the first time in [Koch 1904]. The Curve is constructed stepwise. Beginning from a straight line, there results a meandering curve with strange properties:

- It does not possess a gradient, which means that it can not be differentiated
- The length of any of its sections is always infinite

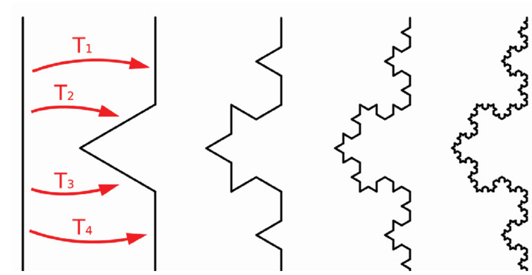

Figure 2: Von Koch Curve

The geometrical construction of the Von Koch curve is iterative, where each of the construction steps consists of four affine geometric transformations. The primitive is a section of a straight line, which is scaled, rotated and displaced by each of the transformations [T1...T4]. Per construction step, four duplicates are generated, of which each will produce four more duplicates in the next construction step.

2.2. ... and Iterative geometric Figures

The strange properties of the aforementioned objects led the mathematicians to name them “monster curves”. In 1981, based on Hutchinson's fixed point theorem [Hutchinson 1981], Barnsley defined a formalism which was able to describe such objects in a deterministic way [Barnsley 1988]. His IFS-method (Iterated Function Systems) consists in a set of functions that are applied iteratively. In our case, a function is an affine geometric transformation. Iterative means that the construction is done step by step. The input of a construction step is the result of the step before.

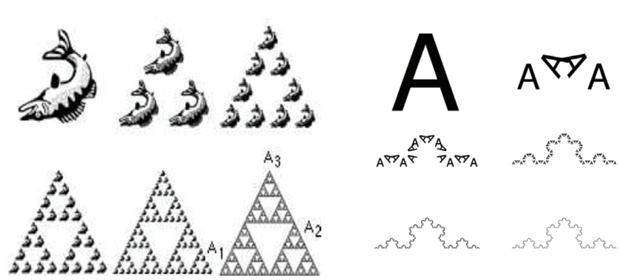

Figure 3: Sierpinski triangle and Von Koch curve according to Barnsley's IFS-formalism

What is really new in Barnsley’s detection is that the resulting geometric figures are not defined by the primitive used, but rather by its transformations. The proof is the construction of a Sierpinski triangle, which uses a fish as primitive. Analogous to this, the Von Koch curve might be constructed based on the letter "A". The result we end up with remains strictly the same.

The conclusion, that it is theoretically possible to use any form of primitive for the construction of such geometric figures, led us to the hypothesis that it is basically possible to use construction elements as primitives. Instead of using fishes like Barnsley, we would rather use construction elements such as beams or panels etc.

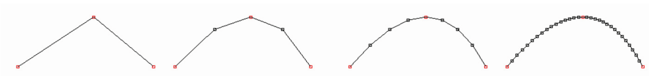

Figure 4: Iterative construction of a Bezier curve

In order to top off the mathematical part of this presentation, we would like to address briefly the Bezier curve. In 1959, De Casteljau discovered a method for the construction today called the Bezier curve. De Casteljau's method is based on iterative construction, which is highly similar to the construction of a Von Koch curve. The actual Bezier curve was analytically described by Bezier in 1961 as a polynomial function, which presents the headstone of today's CAD software.

3 Software Development

3.1. Discrete curve design

The goal is to develop software that makes the design and the production of free-form surfaces easier. Therefore, the software should meet certain topological and geometrical constraints. An important point is that the free-form object will be built out of planar timber panels. According to this, the geometrical constraint demands that the virtual 3D-model must be constituted completely out of planar parts. In order to avoid complex detailing around the corners, we work with surfaces which are entirely composed of quadrilateral faces. This is a topological constraint. On the one hand, constraints will make the physical realization of free-form objects easier. On the other hand, it may limit the design possibilities, and therefore restricts the form-finding process, which we want to avoid as far as possible.

Contrary to actual CAD-software, our program is not based on classical analytical models, which represent free-form surfaces by polynomial functions. The IFS-model studied is more related to subdivision surfaces. Recently, subdivision surfaces show greater interest in the field of discrete geometric design for architectural use [Pottman et al. 2006]. Subdivision surfaces are generally used to build smooth figures, such as cubic B-Spline surfaces. Our model is more general because it is capable of generating not only classical figures, but also rough and fractal figures.

Whether a figure is smooth or rough depends only on the affine geometric transformations. The same curve might be smooth or rough. By changing the subdivision parameters, respectively the smoothness and the roughness can be adjusted. The input of the subdivision parameters is given by the position of what we call subdivision points. Alongside the control points, which are widely known in classical CAD-software, they augment the variety of design possibilities. They provide a graphical way to input the affine geometric transformations, which are expressed in the user-unfriendly form of n-dimensional matrices that work under the skin of the graphical user interface.

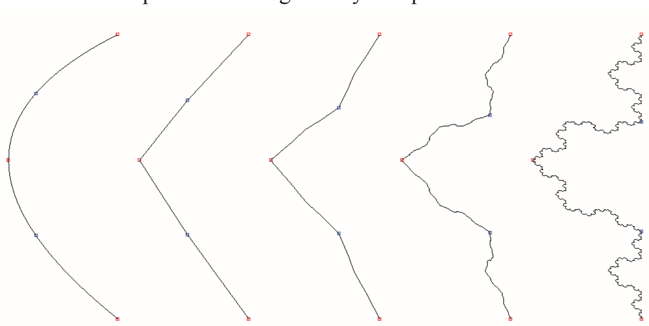

Figure 5: IFS-Curve curve design: Control points (red) and subdivision points (blue)

3.2. A constrained surface model

In order to create iterative surfaces, which are entirely composed of planar elements, we will work on so-called vector sums. Classical CAD-software computes NURBS-surfaces by tensor products, which have the unsuitable property of being composed locally of double curved faces. Great effort is needed for their production. The principle of using vector sums for the generation of free-form surfaces has already been studied by Schlaich [Sclaich et al. 2002]. Such surfaces are combinations of two curves. Figure 6 shows the curves A and B. The vector sum of any two segments of the curves creates a parallelogram, which is part of the entire surface. The surface is completely composed of parallelograms. It therefore meets the geometrical constraint which requires that all its parts must be planar.

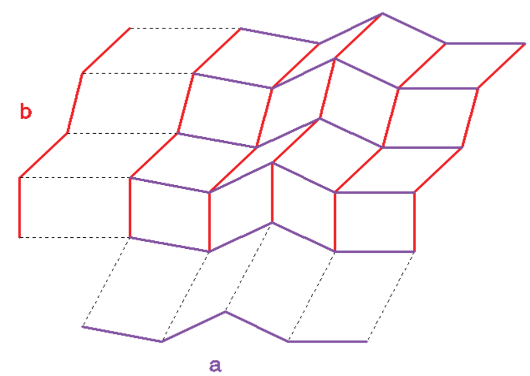

Figure 6: Surface design by vector sum

The design possibilities of vector sums are limited compared to NURBS surfaces. In order to augment the design capabilities, we will employ methods of projective geometry. The IFS-formalism will be extended by the possibility of assigning different weights to its control and subdivision points ($w \neq 1$). The IFS becomes a rational object, where the single weights are not organized necessarily uniformly, but rationally.

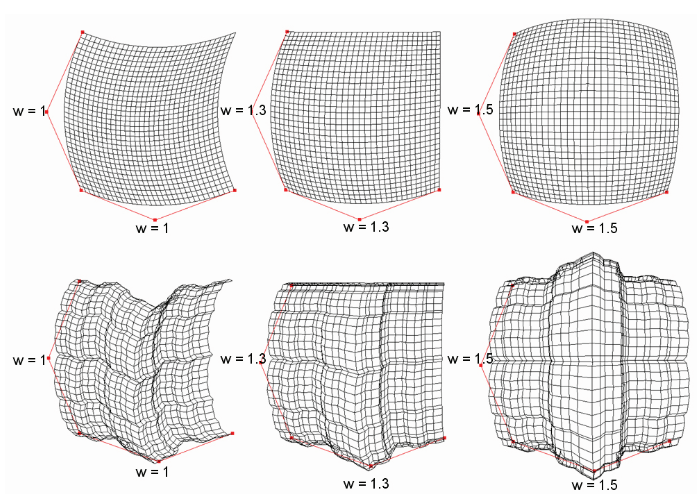

Figure 7: Geometrically constrained rational IFS-surfaces

Iterative geometry offers high design potential. It unifies, in one formalism, the hitherto separate paradigms of the "smooth" and the "rough". Furthermore, it verifies a certain number of geometric constraints, significantly optimizing the production of free-form architecture. This will be shown by examples, below.

4 Applications

4.1. Discrete Bezier vault structure

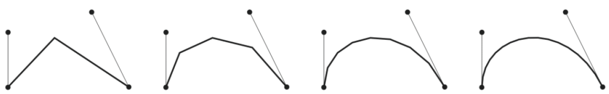

Figure 8: Iterative Bezier Curve

In order to realise physical buildings out of discrete virtual geometries, the elements, which constitute the 3D-models, are replaced by constructional elements. For an iteratively designed curve, the line sections will be substituted by linear constructional elements, such as planks or beams. In the case of a discrete surface, we replace its faces by planar constructional elements (panels, plates etc.). The substitution of geometric elements by constructional elements poses a certain number of questions as the geometric figures do not have physical dimensions like thickness. We will first discuss the more demonstrative case of a two-dimensional figure: the Bezier curve.

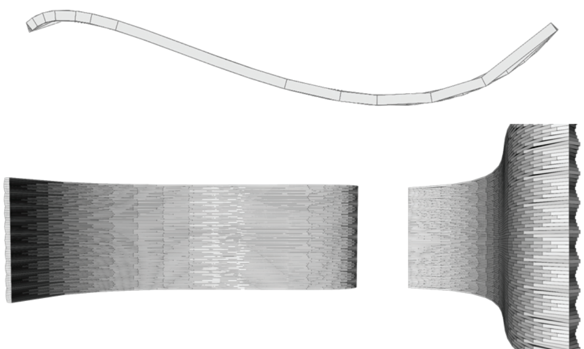

Figure 9: Form Studies

In this example, we build a vault structure based on an iteratively constructed Bezier curve. The line sections which build up the curve will be replaced by raw sawn timber planks. The design of the global shape of the vault can be controlled via the control points. Thereafter, the curve will be subdivided into smaller parts until we will obtain adequate length for the constructional elements. On the one hand, the lengths of the elements should not be longer than the prevalent planks existing on the market. On the other hand, the subdivision should be fine enough to obtain a smooth rendering of the curve.

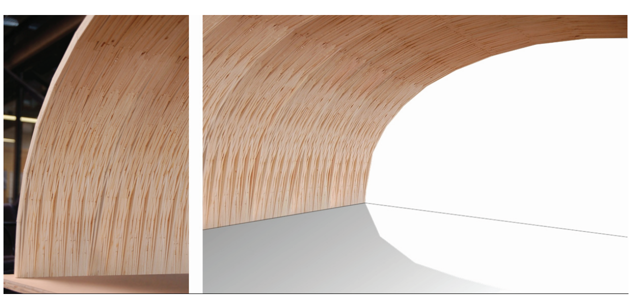

Figure 10: Reduced Scale Model

The relevant dimensions, which are necessary for the production of the constructional elements, are directly induced by the geometric figure. The lengths of the planks correspond to the lengths of the curve's sections. The chamfer angle can also be deduced from the geometric model. The design is therefore limited to two steps:

- Shape control, via the control points
- Subdivision control by choosing the adequate level of iteration

The question of how to partition a free-form object into a coherent set of constructional elements becomes obsolete because it is directly given by the iterative geometrical construction method. The digital chain, from design to production, is inherently optimized. This is an important cost and time factor for the production of free-form architecture.

4.2. Shell structure – feasibility test

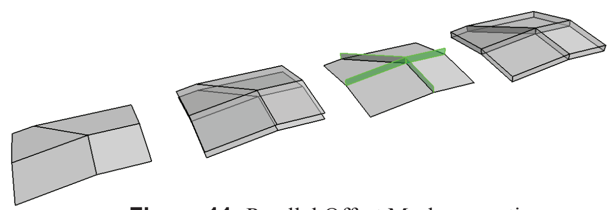

Figure 11: Parallel Offset Mesh generation

We will show below the application of an iteratively constructed free-form surface as a panel construction. In this example, the faces that compose the surface are replaced by planar timber panels. The choice of the thickness of the timber panel is important as the virtual 3D-surface does not present any thickness. A volume model has to be derived from the surface model. First, we generate a parallel offset surface, which holds a constant distance to the initial surface. The distance corresponds to the thickness of the timber panel. Second, the bisector planes are calculated, we will use them later for the chamfer cut of the panels.

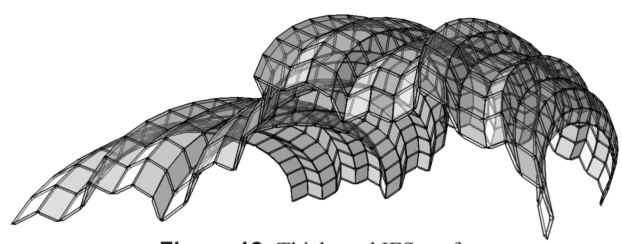

Figure 12: Thickened IFS-surface

In this way, we design free-form objects that are entirely built up of planar constructional elements. In order to test the established digital production chain, we did produce an extract of an iteratively designed free-form surface by a 5-axis CNC-machine. The procedure to get from the geometry to the machine code has been mainly automated. To realize such complex buildings, the following work steps are necessary:

- A unique address for each constructional element is necessary for the logistical reason that the different elements can be assembled in the right place.
- Each element has to be oriented according to the coordinate system of the CNC-machine.

- Automatic generation of the machine code for each element: The material properties, the type of machine and the nature of the cutting tools are of the highest importance for integrated production of the elements, which are all different in size and shape.

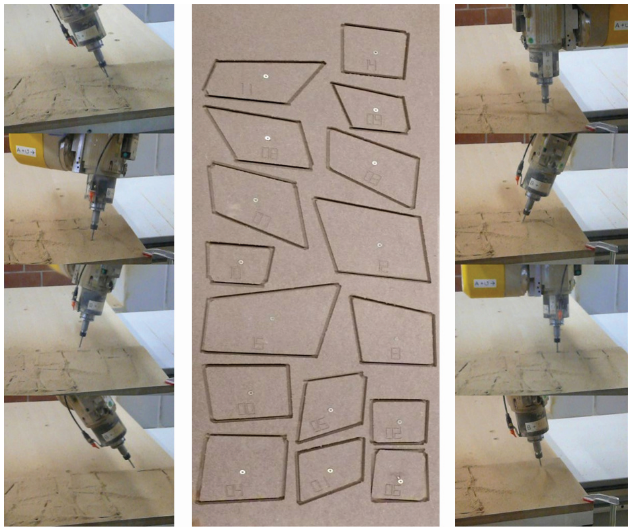

Figure 13: Integrated manufacturing of the constructional elements

4.3. Discussion

The assembled manufactured elements give an accurate rendering of the surface designed on the computer screen. This shows that practical realization of iteratively constructed surfaces becomes possible. It requires a relatively small planning effort. Several problems showed up during the manufacturing process because of the extremely low tolerances permitted by the perfectly fitting pieces. Big scale free-form buildings will probably loosen these tolerances, but the logistics and the montage will probably get more complicated. The efficiency of the method presented is proved insofar as the processing of the data, from design to production, last only a few moments.

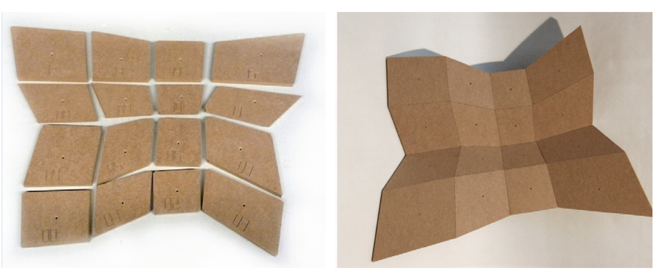

Figure 14: Assembling of the partial prototype

Conclusion

In the future, we will develop bigger and more complex objects. The potential of the new design method for free-form surfaces is far from being exhausted. Applications such as suspended ceilings, free-form facades, climbing walls or halls, await their realization.

Acknowledgements

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Evolving space frames

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Abstract

This paper describes the generation and improvement of space frames populated between two host surfaces. The aggregation of those members is derived from a negotiation process conducted by an Evolutionary Algorithm which takes into account quantifiable architectural and structural aspects.

Keywords: space frame structures, evolutionary algorithm, negotiation

1. Introduction

In this research the space frames become the objective of multi-dimensional negotiations. Instead of utilizing a generic structural type whose parts are subsequently evaluated the entire system is improved. Improvement is regarded as the balance of multiple architectural and structural requirements. The architectural requirements are represented by the double layer surface system. It embodies the desired overall morphology of a roofscape which merges the architectural and the structural system. In addition volumes are defined between the surfaces that should be free from structural elements to provide usable spaces in an architectural sense.

The initial space frame topology (element-node connections) refers to conventional structural systems. The goal of structural improvement lies in the reduction of overall deflection of the system and the use of a minimal number of elements. This objective is assumed to be reached by locally differentiated behavior of the system; double curved areas can generate shell-like behavior which gradually transforms into bending behavior in more planar areas of the system. The space frame is set up as a parametric model whose topology can be altered through external parameter. Thus the boundary conditions are known and the desired goal is clearly defined. The parametric space frame model allows externally driven variation to achieve a solution space instead of a single solution.

2. Evolutionary Algorithm

An adequate means to generate and navigate such a solution space is an Evolutionary Algorithm (EA). Those algorithms are based on mimicry of the process of evolution, which leads to the effect, that through the accumulation of small improvements over time the maintained solutions gradually converge towards the defined criteria. An EA inherits a certain unpredictability, which makes it highly interesting for design processes. When using an EA, the elements of a design model and their properties are defined. But transformation processes, which are performed on the model, do not need to be rolled out in each detail. Of course it is necessary to determine the rules that generate variety. But how it happens in detail, is strongly influenced by the random processes of mutation and crossover. More technically speaking, there are four major types of Evolutionary Algorithms, but which all follow a common architecture, as described by Bentley (Bentley, 1999).

3. The space frame experiment

The environment of the GA is provided by the double-layer surface system. The surfaces represent an architectural design intent developed in a 3D modeling software. Both surfaces are translated into meshes with similar sample rates along their uv parameter space. The proliferation of elements between both meshes will be the objective of evolutionary improvement. Supports can be defined by the user at any node of the meshes in response to the actual design task. The meshing procedure and support definition are not objectives of variation but defined in advance.

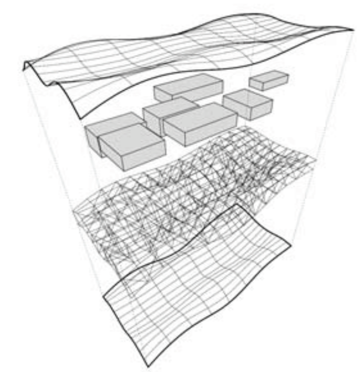

Figure 1: Two surfaces, a space frame and several spaces define the starting conditions.

The objective of evolutionary development is the changing number of diagonal elements between upper and lower mesh. Every node of the upper mesh has two, three or four possible connecting elements depending on its position in the mesh. The actual number of diagonal elements at a node is controlled by a genome. A binary code is directly translated into the space frame topology. A ‘0’ in the genome stands for ‘no element’ while a ‘1’ stands for ‘element’. During initialization a space frame with random topology is generated.

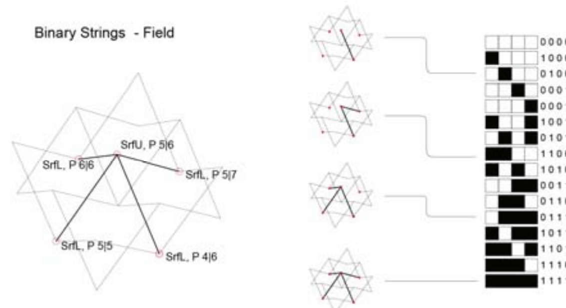

Figure 2: A four digit binary string controls the number of elements at every node of the upper mesh.

The Evaluation/Fitness Functions

In the current experiment the total deflection of the structural system, the total number of diagonals and the number of diagonals that interfere with predefined spaces constitute the fitness criteria.

Structural performance

Each space frame individual is evaluated and ranked by three fitness functions. The first fitness function creates a three-dimensional model in the structural analysis software RSTAB based on the information of the individual genotype. A cross section profile and a material are assigned to each element. Profile cross sections are roughly approximated and cannot be regarded as a proper sizing of the space frame. But of major interest at this moment is a comparison of deflection of the different individuals under the influence of dead load. The maximal nodal deflection is identified and the aspired deflection value of the fitness function is subtracted. This value quantifies the performance of the solution.

Number of elements

The second fitness function simply counts the number of diagonal elements that incarnate in the phenotype. A low number of elements means high ranking. This fitness function obviously constitutes a conflicting interest to the first fitness function which rank rigid structures higher than those which show significant deformations.

Spaces without structure

The last fitness function checks whether an element penetrates defined volumes between the two horizontal surfaces. Three vertices along the element are analyzed regarding their position in relation to the bounding boxes of the volumes that should be free from structural elements for architectural reasons. A low number of intersections leads to higher ranking. The volumes provoke structural disturbances due to architectural requirements which have to be incorporated into the system.

Selection and reproduction

After all individuals of all populations are generated and ranked by the fitness functions the space frames are selected by the roulette wheel method. Thus better ranked space frame individuals will survive more likely but also weaker individuals are not completely without chance. This selection procedure prevents from early stagnation in the development because even weaker individuals may inherit properties that might prove successful in future generations.

The individuals selected by this procedure are used to produce offspring for the next generation. The two genetic operator mutation and crossover vary the number and position of the diagonal elements connecting the upper and lower part of the space frame mesh.

4. Conclusion

The evolved space frame shows an improved performance regarding a significant decrease in element numbers while maintain only little deflection.

The process starts with a high number of elements (406 in generation 1) generating a rigid space frame with a deflection of 103mm. During the evolution the number of elements decreases (298 in generation 280) and the deflection is reduced to ~11mm. The number of element/space intersections is reduced from 300 in generation 1 to 50 generation 280.

The structural system

The series of sections in cross and longitudinal direction of the space frame individual from generation 280 display parts of a system with a very unconventional topology. A systematic arrangement of diagonals is not observable. The allocation seems rather arbitrary. Instead of a preconceived structural typology the system embodies a certain randomness which is owed to the generation process. More important, however, is the remarkable performance of the system; while minimizing the deflections it also reduces the number of elements in total and those that penetrate the spatial volumes.

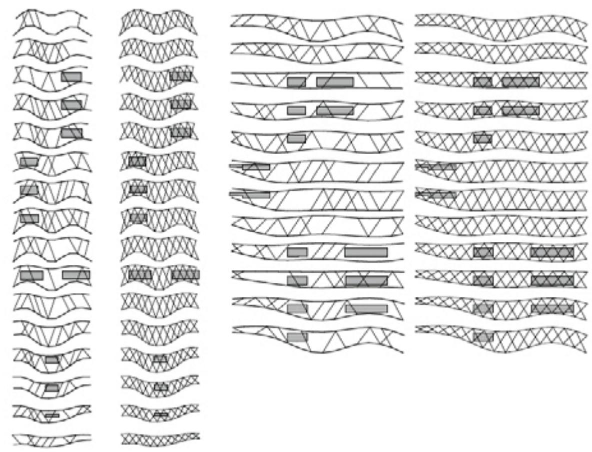

Figure 3: Cross and longitudinal sections of space frame from generation 215 in comparison to space frame with all possible elements.

The system is the best from 5375 evaluated versions. The space frame topology emerges from an interaction with the overall geometry defined by the guiding surfaces and the predefined support positions. While adapting to local conditions the system still maintains an overall coherence. The experiment exemplifies the interaction of the structural system with an overall form intended by the architect and local spatial requirements within the system. Thus it offers a procedure for lively collaborations yielding novel structural and architectural solutions. From the structural perspective the procedure proves successful. The space frame follows double-curved surfaces and is comprised of both, cantilevering and spanning regions. Spaces which should be free from structure further disturb the structure. A generic structural type with repetitive topology would not be a suitable answer to the task. Generating a system in the conventional way by anticipating the behavior of the system and insert structural elements would be a time consuming trial and error procedure. The manipulation of any single element may have repercussions on the entire system.

Improving structural systems through EA's

An EA is utilized to balance multiple requirements. The negotiation between different and even conflicting aspects yields solutions which are improved during the generative process instead of being post-rationalized afterwards. In the experiment the procedure serves as a collaborative design exploration tool for architects and engineers focusing on the structural system which has to embrace architectural design intents. The collaborative design process could be improved by evaluating structural and architectural criteria simultaneously. The equally ranked requirements of maintaining the overall morphology, intermediate spaces and minimal deflections of the space frame could be satisfied.

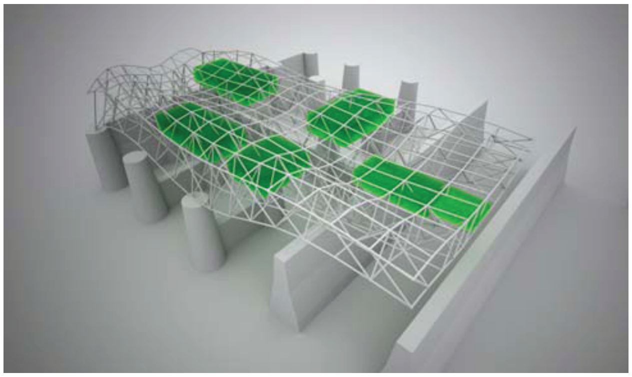

Figure 4: Rendering of the final space frame with boxes representing spaces almost free from structure

The EA in contrast engenders diversity without directed intention. It is not until evaluation that the quality and performance of a solution is revealed. The space frame thus gradually evolves towards a solution which adapts to local requirements. The procedure offers the chance to exceed preconceived notions of structural typologies. To achieve this goal one has to accept a shift in control. The act of steering a design towards a certain direction is relocated from directly envisioning a solution to the definition of selection criteria. The procedure is collaborative because architectural design intents, like the spaces free from any structure, contribute to the ranking of the structural system. The capability of the method to simulate structural behavior is used to turn the analytical tool into a generative one by circularly linking analysis results to generative procedures.

Design exploration

The procedure furthermore embodies an explorative character which is not only interesting for optimization but also in the search for novelty. It is a powerful method to generate diversity within a predefined solution space.

Jane Drake observed that designers tend to approach a complex problem by generating a relatively simple idea to narrow down the range of possible solutions and construct and analyze a first scheme accordingly (Drake, 1978). The quality of a design cannot be anticipated in advance and not all given constraints can be considered in the first proposal. However the early solution contributes to the understanding of the problem itself.

Using an EA in the explorative part of the design process bears some similarities but also differences. One major difference is the need for quantifiable selection criteria. When discussing, sketching, or modeling first ideas the goal is mostly uncertain. Changing the media broadens the range of formal possibilities and always proved helpful in the personal work of the author and when working with students in design studios.

A common notion is seen in the initial generation of early concepts which are far from satisfying solutions. Solutions evolve during a process. The same applies for every design development. Many successful architectural practices are known for their huge amount of scale models build to investigate different versions and variants of one design proposal. Of crucial importance is the difference of a version and variant. Different versions always refer to one initial model or framework. Different variants, in contrast, constitute different ways to approach a design problem. While versions embody a difference in degree variants embody a difference in kind. When it comes to versions of a design proposal the EA is able to outscore conventional design procedures by the sheer quantity. An initial model or framework can be described as a parametric model. In the particular case a parametric model of a space frame structure. Even though this framework will not be exceeded the process of becoming, which yields the series of solutions, can never be skipped.

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Integrated Delivery Empowered by Computational Geometry

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Abstract

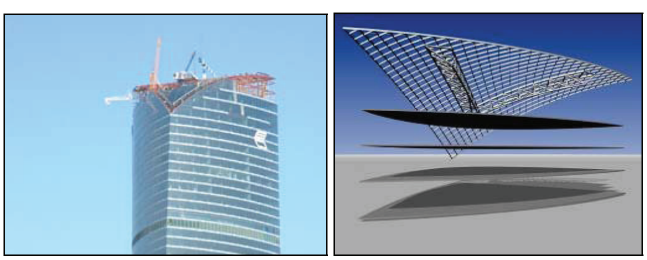
Recent architecture has increasingly been based on and empowered by computational geometry delivered through advanced design software such as Rhino, Catia or Generative Components. In this paper the authors describe a project that applied computational geometry techniques extensively to enable integrated project delivery and allow the project team to keep their design process within limits required for efficiency and precision.

The authors explain how once a geometric process is established it can be leveraged not only throughout conceptual design and form finding, but further utilized for analysis, detailing, fabrication and construction. The example described illustrates benefits achieved from early virtual prototype development, digital integration of interdisciplinary design problems, CNC-based fabrication, modular pre-assembly of components, and efficient installation in the field.

Keywords: parametric and generative geometry, BIM, integrated delivery, TEKLA, digital fabrication

1 Project Description

The project described in this paper is the uniquely shaped, glazed roof cap of the 364m tall Federation Tower in Moscow, Russia. The footprints of the twin-towers are triangular with arc-shaped sides. The smaller Tower B has been topped out by mid-2008 (images 1, left). The taller Tower A is under construction as this paper is written. The form of the tower's vertical envelope tapers as it increases in height. The roof cap, or "Tower Crown", is the intersection of a cylindrical surface with the slanted vertical part of the building envelope. The cap for Tower A is envisioned to be made of glass and steel, as transparent and elegant as possible (images 1, right).

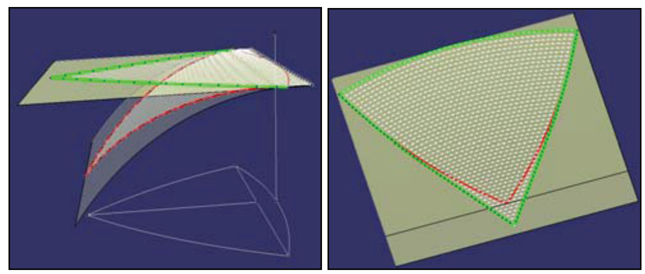


Figures 1: photo during construction of Tower B (left), concept rendering of tower crown for Tower A (right)

2 Geometric Concept

During the early concept phase, the tower crown was described through 2-D CAD documents. It was difficult to communicate the form of the shape of the roof, nor any possible integrated design schemes. The authors felt that the paneling of the roof surface should yield to, maintain and continue all three curved side-lines, as well as integrate with the placement of the outer façade mullions. The goal was to produce an aesthetically pleasing design that was also efficient in a way that can be tied to performance metrics such as weight, cost, complexity, and environmental performance.

Different to the more traditional design process where things are developed on a broader scale first and then progressed into details later, this project almost immediately looks for precision typically seen in the construction document phase to get the complex geometry correct from the start, images 2.

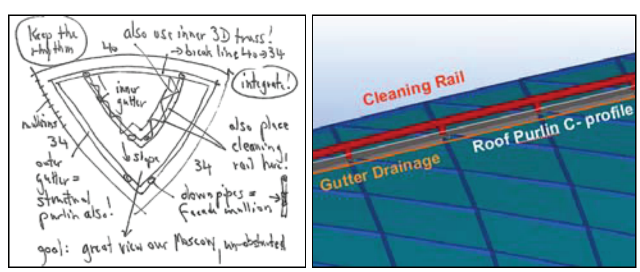


Figures 2: development of geometric concept

3 Adjustment to Specific Project Parameters

After an initial geometric concept was presented the established model framework had to be adjusted to accommodate for various specific project parameters, images 3.

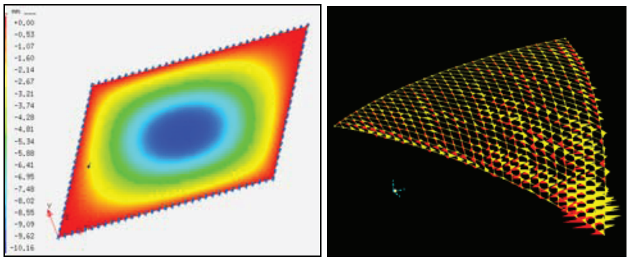
- The mullion points on the sides were not distributed evenly and the number of mullions in the back face was unequal to the number of mullions on the side faces.
- Flat glass panes on flat support vs. straight panes 'forced into bent position' vs. truly bent glass panes on shimmed support.
- Enhanced drainage strategy using an additional recessed gutter line due to large roof slope, fully integrated geometrically and used as a regular structural member.
- Integration of systems for façade cleaning, heating, and lighting.



Figures 3: integration of roof structure with façade and drainage

4 Down-Stream Empowering Analysis

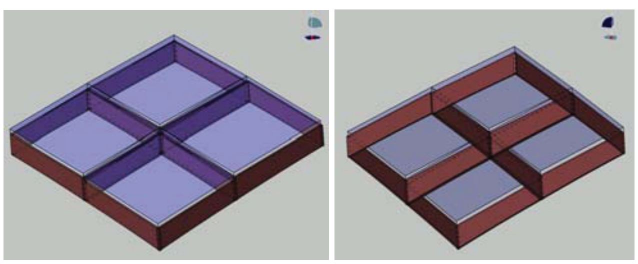
A geometry that was developed based on a computational process naturally allowed rapid generation of various analysis models to design the structural steel, and the mechanics of the glass panes, images 3.



Figures 4: MEPLA analysis to study forcing of glass panels into curved shape (left), structural FEM analysis of roof framing (right)

5 Down-Stream Empowering Detailing

Although all glass panels and all members of the support structure are geometrically unique, their forms follow similar development rules. Designing any "typical" detail in 3-D allowed the generation of parametric components that were then replicated throughout the whole roof grid, image 4.



Figures 5: virtual prototype development of glazing and framing

6 Down-Stream Empowering Fabrication and Assembly

The very advantage of a computational detailing process is that it allows the automated fabrication and pre-installation of all components using CNC-technology. The very fact that all pieces are cut using computerized equipment makes the whole process economically feasible in the first place. Up- front weight estimates of pre- fabricated steelwork portions can be extracted from the virtual prototype, allowing for an early definition of construction joints based on maximum crane lift capacities on site.

Conclusion

Special design projects that display sufficiently complex geometry should be managed using computational geometry concepts. Usage of computational geometry can be beneficial during all phases of the design process:

1. Analysis: automated translation of models speeds up design process.
2. Detailing: scripted procedures reduce geometric errors in virtual model.
3. Fabrication: a 3-D fabrication model improves communication during bidding.
4. Construction: reduces RFI's on site and delivers superior product quality.

Planning of the steel- glass crown of the Moscow Federation Tower demonstrates integrated project delivery empowered by computational geometry. Numerous integration techniques are utilized to meet all esthetic and engineering requirements through one model, which is used not only for all design phases but further into fabrication and erection. The roof structure is due to be built in 2009 and will the tallest transparent roof in Europe.

Rule-based Procedural Reconstruction of NURBS Surfaces for Architectural Exploration

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Abstract

A potential way to bridge the gap between complex form generation and models for physical manifestations is to panelize NURBS surfaces with polygonal faces. This paper investigates the transition from NURBS surface to a mesh solid through a procedural modeling approach illustrating how a discretized planar surface can be reconstructed for form generation and exploration. The paper promotes this approach as an efficient way to modeling complex forms using an example drawn from real life architecture to demonstrate a generative process with restructuring through, potentially customizable, rules.

Keywords: rule-based, surface reconstruction, architectural exploration.

1 Introduction

Parametric modeling is bound to constraints that regulate geometry. Killian [2006] takes a bidirectional perspective to exemplify the potential of modeling design with associative constraints. Moustapha [2005] proposes a formal expression to describe the transformative and recursive nature of constraint applications for form exploration. In general, these constraint-based approaches associate geometric components with prescriptive parameters. However, modeling a sophisticated form, such as a freeform solid, demands a technique typically of the kind derived from Non-Uniform Rational B-Splines (NURBS). For purposes of construction and/or fabrication, the NURBS surface is usually reconstructed as a triangular, quadrilateral, or perhaps, a multilateral polygonal mesh. The challenge of restructuring a NURBS surface into a meshed object requires processing the underlying geometry.

In this paper, we illustrate an approach to reconstructing NURBS surfaces using a simple subdivision scheme. The scheme encompasses formal expressions and operations on nodes to generate subdivision meshes, and also, on organizing successive meshes to form the ultimate surface structure.

The focus in this particular work is to make the subdivision scheme customizable to users for further geometric exploration. Ultimately, the goal is to extend this approach to architectural exploration, to make the modeling process generative and more flexible. We demonstrate this using a modeled surface, inspired by the work of Santiago Calatrava, on which the resulting generative reconstructions are illustrated.

1.1. Problem Statement

The problem is to create a surface structure, a mesh solid, from a given NURBS surface with zero depth. We propose a grammatically based procedural modeling approach coupled with a formal re-meshing process. There are precedents for both.

One of the earliest and better known formalisms is L-system developed by Aristid Lindenmeyer in 1968, which has been successfully applied to plant modeling and visualization [Prusinkiewicz and Lindenmeyer 1990]. Basically, it is a string grammar, with rules specifying symbols, variables and transformations. The growth process of plants is simulated by recursively applying rules. More recently, Muller et al. [2006] extend another grammar formalism, shape grammars [Stiny, 2006], to a technique aimed at urban modeling. In their approach, buildings are created grammatically, through representations from volumetric mass to building facades, so as to mimic the complex environment of a city.

Recently, there has been interest in employing re-meshing techniques for architectural applications to support complex form generation. In particular, quad meshing has been proposed for structural modeling [Pottmann et al. 2007]. Liu et al. [2006] developed PQ meshes, which are quad meshes with planar faces, to discretize curvilinear surfaces. A re-meshing application by Culter et al. [2007] addresses issues of fabrication and topological coherence via a clustering algorithm, and interactions between designer and the re-meshing process. Akleman et al. [2004, 2005] implemented a topological mesh modeler to support innovative sculpture generations. A common theme underlying these various developments is the reconstruction of the original mesh, by certain geometrical operations, to propagate more sophisticated forms.

2 A procedural approach for reconstructing architectural geometry

The general workflow for reconstruction starts by discretizing input NURBS surfaces as polygonal meshes. This initial stage serves as the basis for subsequent geometric reconstruction and is controlled by the specified number of meshes. Alternatively, we can regard the meshed object as input to the reconstruction scheme independent of where it originated from. The reconstruction scheme is defined by a number of parameters that reflect the inter-relationships from predecessor to successor shapes. The reconstruction stage is interactive, where, potentially, designers sketch out their intentions on structuring the underlying geometry. The reconstruction procedures are then applied to the discretized meshed surface to produce alternative designs. Figure 1 illustrates the workflow.

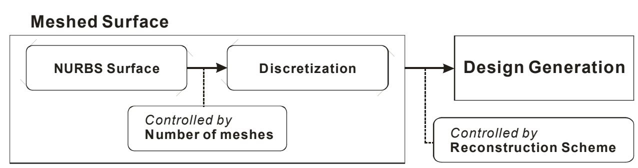

Figure 1. Workflow for processing architectural geometry.

2.1. Reconstruction Scheme

For the remainder of this paper, we assume that we are working with quadrilateral meshes. The following process is then basic: each quadrilateral face of a given discretized quad mesh surface is potentially replaced by a number of alternative quadrilateral faces. This process is dominated by a modeling procedure that specifies a hierarchical relationship from predecessor to successors. The modeling procedure, namely, a subdivision scheme with customized tuning parameters, is the reconstruction scheme.

Notation: Each quadrilateral face is represented as: *face*:$\{v_1, v_2, v_3, v_4\}$, where "*face*" represents the quadrilateral mesh and v_1, v_2, v_3, v_4 are the mesh vertices representing the face in counter-clockwise order.

Figure 2 illustrates three different quad faces (shaded areas). The original input, *face*:$\{A, B, C, D\}$, is shown on the left hand side. *Face*:$\{T_1, B, T_2, D\}$ and *faceSet*(2):$\{\{A, B, T_1, D\}, \{B, C, D, T_2\}\}$ are alternative meshed faces that can be produced. The transition from one face (the input mesh quad) to single or multiple faces specifies a reconstruction scheme. Note that the face can be either convex or concave.

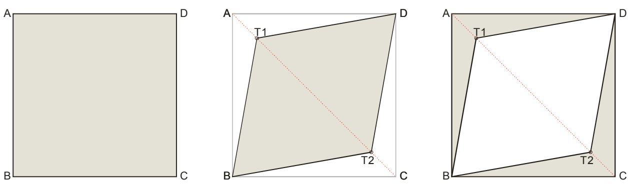

Figure 2: (*Left*) *face*:$\{A, B, C, D\}$; (*Middle*) *face*:$\{T_1, B, T_2, D\}$; (*Right*) *faceSet*(2):$\{\{A, B, T_1, D\}, \{B, C, D, T_2\}\}$

For example, the reconstruction from *face*:$\{A, B, C, D\}$ to *face*:$\{T_1, B, T_2, D\}$, represents a replacement, where nodes A and C are replaced by T1 and T2 respectively. To achieve this, two simple rules, the vertex and face rules are defined. The vertex rule creates a new vertex, and the face rule replaces the original face by one or more new faces.

2.1.1. Vertex Rule

The vertex rule, given by (1), takes, as the input, three parameters, vertices v_1 and v_2 and weight w and creates a new vertex, *newV*, as a linear combination of vertices v_1 and v_2, specified by the weight, w.

$$newV\,(V_1, V_2, w){:}\ V_1 * w + V_2 * (1 - w) \qquad (1)$$

2.1.2. Face Rule

This rule specifies the replacement of a quad face by a list of quad faces and takes by the following general form:

face:{*vertices* …} ~>
faceSet(*num*):{ *face*:{ *vertices* …}, …, *face*:{*vertices* …}}

Here the left most "*face*" is the quad face that is to be replaced by "*faceSet*(*num*)," a list of quad faces. "*num*" is the number of faces in this set.

For example, consider the rule

$$face{:}\{A, B, C, D\} \sim> faceSet(3){:}\{ face{:}\{A, B, T_1, D\}, face{:}\{B, T_2, D, T_1\}, face{:}\{C, D, T_2, B\}\} \qquad (2)$$

The original face, $\{A, B, C, D\}$, is replaced by three successive faces, $\{A, B, T_1, D\}$, $\{B, T_2, D, T_1\}$, $\{C, D, T_2, B\}$, by newly defined vertices T_1 and T_2, which are derived from vertices A and C.

We can combine the two rules and reconstruct the face. Applying rule (2) to *face*:$\{A, B, C, D\}$ generates the set, {*face*:$\{A, B, T_1, D\}$, *face*:$\{B, T_2, D, T_1\}$, *face*:$\{C, D, T_2, B\}$}shown in the middle of Figure 3. If we then apply the same rule to *face*:$\{B, T_2, D, T_1\}$ we generate three more faces, { *face*:$\{B, T_2, T_3, T_1\}$, *face*:$\{T_2, T_4, T_1, T_3\}$, *face*:$\{D, T_1, T_4, T_3\}$}. After two iterations, *face*:$\{A, B, C, D\}$ has been replaced by five faces, {*face*:$\{A, B, T_1, D\}$, *face*:$\{B, T_2, T_3, T_1\}$, *face*:$\{T_2, T_4, T_1, T_3\}$, *face*:$\{D, T_1, T_4, T_3\}$, *face*:$\{C, D, T_2, B\}$}, shown on the right of Figure 3.

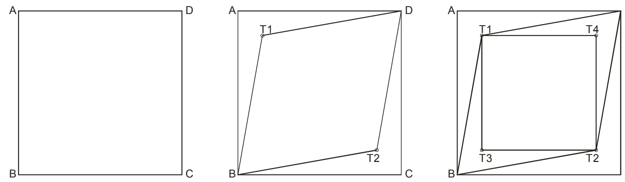

Figure 3: (*Left*) *face*:$\{A, B, C, D\}$; (*Middle*) *faceSet*(3):{{*face*:$\{A, B, T_1, D\}$, *face*:$\{B, T_2, D, T_1\}$, *face*:$\{C, D, T_2, B\}$}}; (*Right*) *faceSet*(5):{ *face*:$\{A, B, T_1, D\}$, *face*:$\{B, T_2, T_3, T_1\}$, *face*:$\{T_2, T_4, T_1, T_3\}$, *face*:$\{D, T_1, T_4, T_3\}$, *face*:$\{C, D, T_2, B\}$}

2.1.3. Fenestration Function

Using the two rules above, we have a subdivision scheme for face reconstruction. We can add a function to control the visibility of every face so as to create openings from them. For example, consider the notation:

Fenes(*Num*):{*Boolean*, … , *Boolean*}

"*Fenes*" is the function identifier with "*Num*" number of Boolean values contained in the list. Each Boolean value maps to a corresponding face. The visibility of each face is turned on or off, according its value, 1 or 0, in the list. As Figure 4 illustrates, two different fenestration rules applied to the same set of faces generate different configurations.

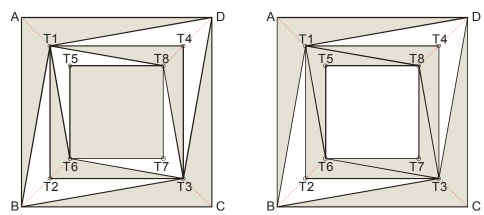

Figure 4: (*Left*) *Fenes*(9):{1, 0, 1, 0, 0, 1, 0 , 1, 1}; (*Right*) *Fenes*(9):{1, 0, 1, 0, 1, 1, 1, 1, 0}; Shaded regions are solid faces, others are empty.

By varying the visibility of each polygon face, we can generate alternative surface structures with ease. Moreover, surface planarity, under mesh reconstruction, is maintained to be the same as the original. By doing so, the topological structure of the surface remains unchanged and only regional geometrical details are added. Notwithstanding, the outcomes derived from the reconstruction schemes can make interesting changes to the final appearance.

2.2. Post Processing: Face Extrusion

After reconstructing the input surface, a post-processing procedure is suggested. This process involves a mesh offset operation on the polygonal faces and makes the surface with zero depth become a more realistic solid artifact, a panelized surface structure with thickness. We can create offset meshes along each face normal by a given distance "D", as shown in the Figure 5. In this way, a solid volumetric surface can be created.

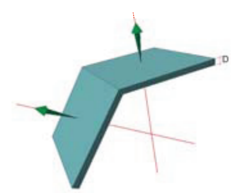

Figure 5: Offsetting the surface by a given distance D.

Despite its relative simplicity, this step can make a surface appear more like a real architectural piece, as shown in the Figure 9.

3 A Surface Reconstruction Example

An architecture example taken from one of Architect Santiago Calatrava's projects in 2000 was remodeled. The project, Windery Complex for the Bodega & Bebidas Group, features a curved roof composed of elementary rectangular tubes, as shown in Figure 6. We remodeled the curved surface of the roof as an example to explore potential variations by the procedural reconstructing schemes presented in this paper.

Figure 6: Image after Windery Complex for the Bodega & Bebidas Group by Architect Santiago Calatrava, 2000

The initiated surface, created using NURBS, is illustrated in Figure 7. Although NURBS model complex freeform objects as mathematical representations, for the practical purposes, such as manufacture or fabrication, NURBS-based objects are usually are panelized. Motivated thus, we discretize the surface as quadrilateral meshes. Other meshes are possible, for instance, triangular meshes possess the same type of geometric information, including nodes, edges, planes etc. However, in this work, we considered only quad faces. The number of quad meshes to replace the original NURBS surface controls the discretization. For this experiment, this number is set to 1000.

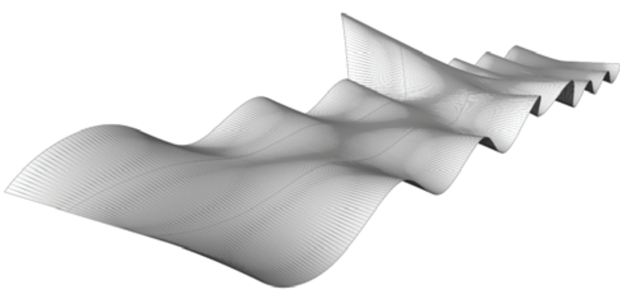

Figure 7: The original NURBS surface

Initially, we applied the reconstruction scheme without any post face-offset operation and generated the final structure, shown in Figure 8. The reconstruction scheme applied here is the second iteration shown in Figure 3, in which the original face is replaced by the set with five faces. Also, the fenestration is represented as *Fenes*(5):{1, 1, 0, 1, 1}.

For the last step, we took the reconstruction scheme illustrated on the right in Figure 4, which has total 9 faces in the set and we assigned an arbitrary distance for the face offset operation. The generated structure is shown in Figure 9. This reconstructed mesh solid demonstrates how a NURBS surface is faceted with a customized pattern.

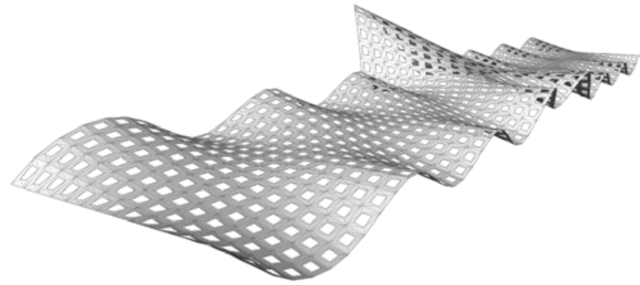

Figure 8: Surface derived from the reconstruction scheme comprising face and fenestration rules: (1) *face*:{*A*, *B*, *C*, *D*} ~> *faceSet*(5):{*face*:{*A*, *B*, T_1, *D*}, *face*:{*B*, T_2, T_3, T_1}, *face*:{T_2, T_4, T_1, T_3}, *face*:{*D*, T_1, T_4, T_3}, *face*:{*C*, *D*, T_2, *B*}; and (2) *Fenes*(5):{1,1,0,1,1}.

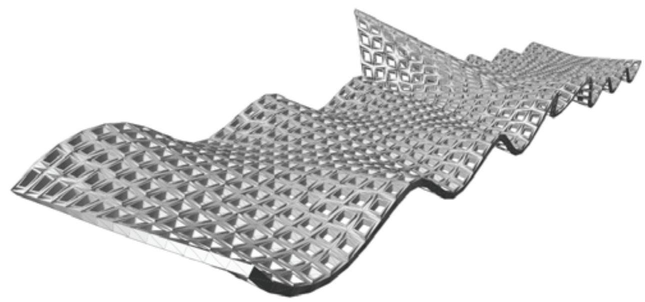

Figure 9: Surface derived from the reconstruction scheme and a post face-offset. Reconstruction scheme comprises the following face and fenestration rules: (1) *face*:{*A*, *B*, *C*, *D*} ~> *faceSet*(9):{*face*:{*A*, *B*, T_1, *D*}, *face*:{*B*, T_2, T_3, T_1}, *face*:{T_2, T_3, T_6, T_1}, *face*:{T_3, T_8, T_7, T_6}, *face*:{T_8, T_5, T_6, T_7}, *face*:{T_1, T_6, T_5, T_8}, *face*:{T_4, T_1, T_8, T_3}, *face*:{*D*, T_1, T_4, T_3}, *face*:{*C*, *D*, T_3, *B*}}; and (2) *Fenes*(9):{1, 0, 1, 1, 0, 1, 1, 0, 1}.

It should be noted, for purposes of implementation, that during the generative process, the input NURBS surface, its discretized meshed surface, and its final structured mesh solid are linked in a directed graph. Associative geometric relations between different generations are maintained through intermediate data nodes. In this way, up-to-date information can be maintained as changes occur.

4 Discussion and Conclusion

Our current work focuses on formalizing an approach to geometry reconstruction. The example here uses an input NURBS surface. We are currently experimenting with a similar approach on surface initiations, which is expected to replace the first NURBS surface creation and make the whole process smoother. Our ultimate objective is to extend the generative process from surface initiation to detail reconstruction. This will benefit the representation of the entire design model using a constrained associative network and render generative control to designers for further formal exploration. Currently, the system is executed through scripting commands. We have plans to provide a graphical user interface to support visual and more responsive interactions for designing reconstruction schemes.

Admittedly, the approach in this paper is not without criticism from the perspective of real designs. For instance, it lacks any consideration of structural, material, or performance aspects. However, we expect that once an underlying geometry can be processed and organized coherently, other computational tasks become easier to handle. Another is that the approach is procedural, that is, programming-oriented, and this may distract designers from their initial design activity. Yet, the knowledge and ability to control modeling procedures and parameters must be regarded as the foundation by means of which the computational requirements of subsequent design applications can be addressed.

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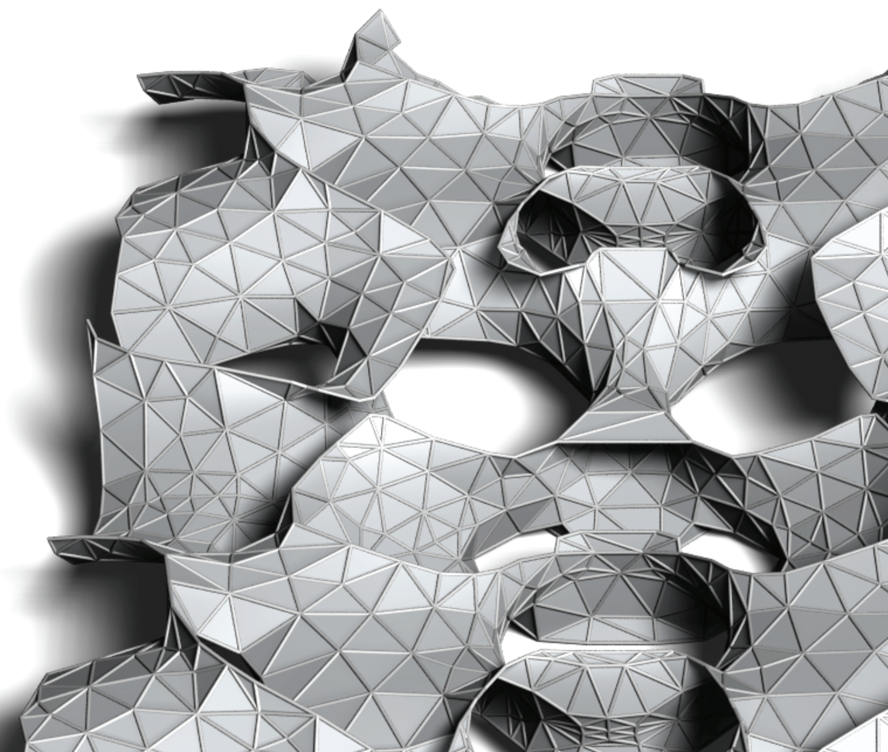

Geometry lies at the core of the architectural design process. It is omnipresent, from the initial form-finding stages to the final construction. Modern geometric computing provides a variety of tools for the efficient design, analysis, and manufacturing of complex shapes. On the one hand this opens up new horizons for architecture. On the other hand, the architectural context also poses new problems to geometry. Around these problems the research area of architectural geometry is emerging. It is situated at the border of applied geometry and architecture.

This symposium brought together researchers from the fields of architecture and geometry to discuss recent advances in research and practice and to identify and address the most challenging problems. We connected researchers from architectural practices and academia. The event consisted of two parts, two days of hands-on workshops followed by two days of oral and poster presentations in conference style, featuring prominent invited speakers.

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