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].

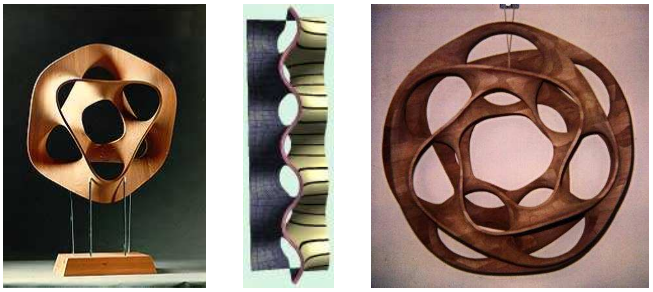

Figure 1: (a) *Hyperbolic Hexagon*, (b) 7-story *Scherk Tower*, (c) *Heptoroid* (seven 4th-order saddles).

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).

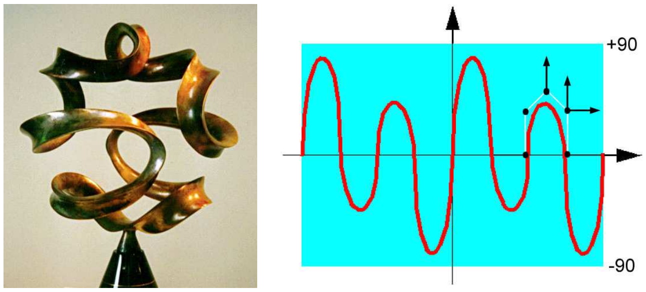

Figure 3: (a) *Pax Mundi*, (b) modulated 4-period Gabo curve.

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).

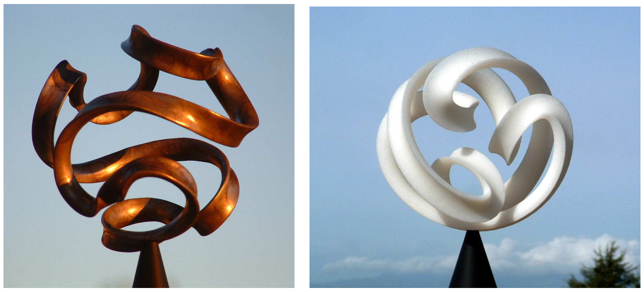

Figure 4: (a) *Via Globi - Maloja*, (b) *Music of the Sphere*.

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.

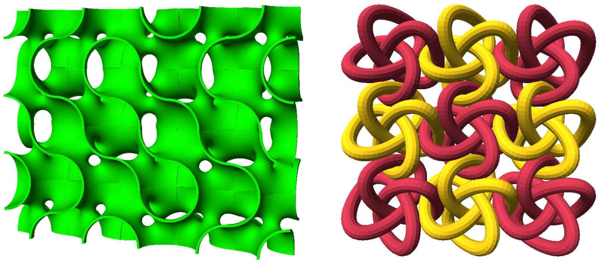

Figure 6: (a) *Volution*-wall, (b) Knot-wall.

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.

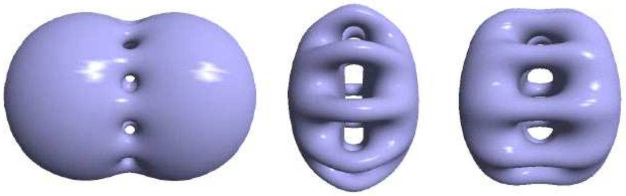

Figure 7: (a) MES, (b) MVS, and mixed optimization functional.

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.

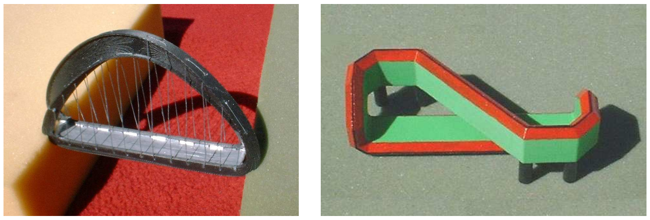

Figure 8: (a) *Moebius* bridge; (b) *Moebius* building.

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.

References

Brakke, K. 1992. Surface Evolver. *Experimental Mathematics*, Vol. 1, no. 2, pp. 141-165.

Brakke, K. 2000. Triply Periodic Minimal Surfaces. http://www.susqu.edu/brakke/evolver/examples/periodic/

Collins, B. 1997. Evolving an Aesthetic of Surface Economy in Sculpture. *Leonardo*, Vol. 30, No. 2, pp. 85-88.

Collins, B., Reinmuth, S., Schwalbe, D., Séquin, C. H., Wagon S. 2003. Whirled White Web: Art and Math in Snow. *Meeting Alhambra, ISAMA/BRIDGES*, Granada, Jul.23-25, pp, pp 383-392.

Hauer, E. 2004. *Continua – Architectural Screens and Walls*. Princeton Architectural Press.

Joshi, P. and Séquin, C. H. 2007. Energy Minimizers for Curvature-Based Surface Functionals. *CAD Conference*, Waikiki, Hawaii, June 25-29, pp 671-681.

Moreton, H. and Séquin, C. H. 1992. Functional Optimization for Fair Surface Design. *Proc. of SIGGRAPH'92*, pp. 167-176.

Reinmuth, S. 2000. Bronze Casting of Geometrical Sculpture. *MOSAIC*, Seattle, WA, pp 209-214.

Scherk, H. F. 1835. Bemerkungen über die kleinste Fläche innerhalb gegebener Grenzen. *J. Reine Angew. Math. (Crelle's Journal)* 13, pp 185-208.

Séquin, C. H. 1997. Interactive Generation of Scherk-Collins Sculpture. *Symposium on Interactive 3D Graphics*, Providence RI, pp. 163-166.

Séquin, C. H. 2003. Volution's Evolution. *Meeting Alhambra, ISAMA/BRIDGES*, Granada, Spain, Jul.23-25, pp 13-24.

Smith, J. 2003. SLIDE design environment: http://www.cs.berkeley.edu/~ug/slide/docs/slide/spec/