The topological design of sculptural and architectural systems

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INTRODUCTION

In my work over the past 12 years I have consistently created systems with an approach which I will describe as topological design. I have tried to capture the spirit of this work in my film, "The Ron Resch Paper and Stick Thing Film," which will be shown elsewhere in the conference. I would like to present here, and in a color slide presentation, the concept of topological design using examples from my work for clarity. I will show how the conception and fabrication of designed objects have a topological and a geometric aspect. Currently, these objects may be characterized as emphasizing the geometric aspect, by limiting an entire class of objects to be a unique one. Finally, I will show where the introduction of the computer into design and production process makes possible the topological aspect, so that the automation of custom made objects might replace a series of identical 'ready mades.'

HISTORICAL BACKGROUND

Before the Industrial Revolution, one imagines that manufactured objects were made by that commonly named group of people, the "Smiths." The blacksmith, the silversmith, the locksmith, and the gunsmith were the craftsmen that made the objects of daily living. The smithery, and the objects it made, emerged from, and were maintained by, an immediate collection of patrons whose wants and needs it satisfied. The legacy handed down by tradition was not just the object itself, nor was it the object and its smithery as caretaker. It was a symbiosis of user, object, and maker that lived together in very close communication, both in time and in space.

The gunsmith, for example, possessed a "soft prototype" in his intimate and complete understanding of a gun. That his concept was topological is clear, from his ability to accommodate the varying needs of his users by varying the design of a gun to fit the user. The grip could be made a little heftier, the barrel a little longer.

Industrialization came with the desire for greater volume. The inherent understandings of one man, in touch with his craft and his patron, gave way to an expansive fragmentation of this intimate process. The fragmentation of implicit functions into explicit roles to be played by many persons and machines, brought with it an incredible communications problem.

In response to this, there came standardization and regimentation. The varying needs of the user were averaged by the researcher, the designer, and the engineer, and frozen into a "hard prototype." The responsive variations of the craftsman were replaced by a cumbersome and complex organization that seems to be a patchwork of stop-gap measures, with a commensurate growth of communications problems.

The introduction of the computer into this complex set of relationships, as the greatest and fastest of machines, may only lengthen and slow down the communications process. Its introduction as a medium of communication, however, could bring together the maker, the object, and the user into a cohesive whole once more. My work in structure design has produced the following concepts and structures which make this seem plausible.

PERSONAL BACKGROUND

In 1961 I began examining wadded sheets of paper and trying to understand the random folding that occurred. My desire was to understand what sculptural forms were possible. The study limited the possibilities from the outset by two highly controlling restrictions:

1. Only folding of the flat sheet was allowed, i.e., no cutting or gluing.
2. The folded edges were forced to be straight line segments; no curves.

With these restrictions as goggles and blinders, I looked at a wadded sheet for randomly occurring wrinkles of interest. I selected several patterns, diagrammed them on a separate sheet in accordance with the imposed limitations, and folded them. Each of these forms had visual appeal, but was seemingly unrelated. The search was for something that had both conceptual and visual appeal. In an attempt to achieve this I was influenced by the classic...
Consequently, I decided to impose a third restriction in the form of a question. It was the key to a rich set of possibilities. Could these simple forms be replicated through symmetry operations into a single folded surface which would be an expanse of delicate and intricate folds? Could I rearrange the folding diagrams of these elementary forms such that when combined with symmetry operations they would create two-dimensional mosaic patterns? The folded paper dome in Figure 1 was the first structure resulting from these restrictions.

I was pleased with this first folded paper form, even though I understood it to be only one of a class of forms. This led me to ask, how many ways could I change the scoring pattern? How would variation in a particular scoring diagram affect the three-dimensional folded structure? What were the limits within each class of change? Before introducing the structures which resulted from these questions I will describe a classification scheme for man-made objects. While the scheme is broadly applicable, I will focus on architectural structures including my own.

GENERATING SYSTEMS

The geometric surfaces employed in architectural design are typically the plane and the sphere. When one wished to build a network approximation to these ideal surfaces, or more complicated ones, a generating system is required. A generating system is defined with the existence of two associated rules which describe:

1. How to determine the geometry of each part
2. How each part is assembled into the system

Following are three classifications for generating systems: combinatorial, geometric and topological.

COMBINATORIAL GENERATING SYSTEMS

A combinatorial generating system has a part rule which determines a finite set of elements, and which allows for each to be replicated. Its rule for connectivity is not definitive, but is permissive within contextual constraints by allowing the user to combine the parts in various ways to form a single system. The geometry of the part, or syntactic rules, may dictate these constraints of part connectivity. Some examples of this would be the letters of the alphabet, modular architectural systems and certain constructional toys, such as Tinker Toys.

GEOMETRIC GENERATING SYSTEMS

As most structural systems in architecture are composed of parts arranged in triangulation, it is more revealing to look at the rule for determining the geometry of the part rather than its connectivity rule. Two types of architectural structure which make this consideration clearly relevant are flat space frames and domes.

The shape of most architectural roof systems is flat, whether the system be horizontal or inclined. Space frames are often used where a large free-span, (uninterrupted by supports), is required. Of the many space frame geometries used, the "octet-truss" (composed of octahedrons and tetrahedrons), is the most common. It has the simplest part rule: cut all the pieces the same. It is not surprising that the simplest structure has the simplest rule. This simplicity contributes to its popularity. Such a flat structure was assembled into the well-known
pattern at the bottom of Figure 8. One can note that the identical pieces in this structure are equilateral triangles, the structure being more commonly fabricated from rods of equal length.

The part definition for domes, however, requires a more complicated rule resulting from a geometric impossibility. It is impossible to transform a regular network of triangles, squares, or hexagons onto a domed surface without distortion. The regular network is usually transformed to fit a dome by a relative expansion of the interior and relative contraction at the outer edges. What distinguishes various dome designs is the method used to distribute the network on the dome surface, and the surface shape permitted.

Of the several generating systems for the geometry of a dome, the geodesic system has become the most publicized. It combines the geometry a regular polyhedra, the icosahedron, with the transformation of a triangular network onto a sphere.

The transformation rule patented by Fuller* determines that consecutive nodes of the network will lie along great circle arcs of the sphere. Thus, it borrows its name and method from classical geometry where a geodetic line on a sphere is defined to be a great circle arc. This means, of course, that the shape of geodesic domes is limited by its defining rule to be sections of a sphere. Also, Fuller's geodesic system has somehow achieved a popular misconception, that the triangles composing its surface are all equilateral triangles relative to each other makes possible a rigid body motion of the triangular parts, while also determining a unique part geometry for each of the parts. The shape of the total system may become rigid by fixing the angular relations between the parts at the boundary of the system alone, or by fixing these angular relations throughout the entire system.

To make a continuous transformation of this space maintains connectivity while changing the geometry, i.e., the size and shape of the system parts, the simplest of these transformations is the "ribbon transformation," which increases or decreases the width of the "ribbon" while not altering the size or shape of the remainder of the mosaic. The effect of this transformation can be seen in Figure 2 where three intersection "ribbons" of the mosaic are being decreased to a zero width.

Secondly, there is the three-dimensional space in which a folded structure may be varied by folding. The triangles resulting from the topological transformation are connected to each other in such a way that each edge is an axis of folding. Thus the folding of the individual triangles relative to each other makes possible a rigid body motion of the triangular parts, while also determining a continuous, geometric transformation of the entire system of parts. The shape of the total system may become rigid by fixing the angular relations between the parts at the boundary of the system alone, or by fixing these angular relations throughout the entire system.

Therefore, the selection of a distinct folded pattern from the topological space of a foldable mosaic will determine an entire class of structures, the members of which are a rigid instance of the dynamic folding of its specific mosaic pattern. This can be seen by comparing the top module of Figure 2 with the folded form created from it, shown in Figure 1.

For further illustration, pick the bottom module from the topological space of Figure 2. Repeat this pattern in defining its connectivity to other parts. The first rule is geometric in nature and the second rule, as here defined, I would characterize as topological.

There is no need for a duality in viewing a designed object as a system of parts, but it is useful to focus attention on an object's quantitative aspects separate from its qualitative aspects. In the field of geometry, topology has been defined as the geometrical theory of situation without respect to size or shape. The popular definition is rubber sheet geometry. I will use topology to describe the continuous transformation of a system that may preserve only the connectivity of its parts. A topological generating system is a generating system whose rule of connectivity and whose set of parts remain constant, while a continuous transformation varies the geometry of its parts, or some subset thereof.

TWO LEVELS OF CONTINUOUS TRANSFORMATION FOR FOLDED STRUCTURES

My concern in the design of structures has been with the continuous transformation of the parts of a system. This concern is the basis for my concept of topological design. Some structures designed with this concept reveal that there is a two-level hierarchy of differentiable spaces; one traced out by a topological transformation, the other by a geometric one.

First, there is the two-dimensional space of the mosaic in which the scoring pattern may be varied topologically. A continuous transformation of this space maintains connectivity while changing the geometry, i.e., the size and shape of the system parts, the simplest of these transformations is the "ribbon transformation," which increases or decreases the width of the "ribbon" while not altering the size or shape of the remainder of the mosaic.

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* R. Buckminster Fuller, Patent 2,682,235, June 29, 1954
the plane; and fold. One instance of the class of realizable structures from this pattern is Figure 3.

Christiansen has written a computer program to simulate the folding transformation.\* It was used to compute the geometry in the sequence of computer simulated video pictures of Figure 4. It is evident from this sequence that a single scoring pattern may be continuously transformed by folding, to achieve a wide variety of architectural surfaces.

I have discussed the two levels of transformation (the topological and the geometric) which may be performed upon a "folding mosaic" of the two-dimensional plane. The combined transformations produce a continuum of physically realizable structures, from which a designer may select a specific architectural shell form, by specifying his needs.

FOLDING MOSAICS AND MODULAR FOLDINGS

The two levels previously described are imbedded within two more. While the first two levels are sets whose members exist in a continuous space, the members of the remaining two levels exist in a discrete space. They are:

1. The set of all folding mosaics of the plane*
2. The set of all modular foldings of the plane

Above, I have shown one of my "folding mosaics" and allowable transformations of it. Many others may be seen in my film previously mentioned. This set may be included within a set of modular foldings of the plane. It will include modular foldings which are not infinite, two-dimensional patterns, but are limited by their definition to some local, finite graph whose modules are interrelated by a rule. I will describe one example of this set which was published as the cover design of the "Communications of the ACM" for November, 1970.

This structure is named "bird form," as I have used it most often to create abstract, bird-like shapes. As in the folded mosaics, the scoring diagram for the bird-form has its associated topological transformations for which I have written a computer program with parameterized input. Each parameter controls a class of continuous topological change to the scoring diagram.

Some of the classes of change are depicted in Figure 5. From top to bottom they are:

1. Proportions of the "page" before subsequent transformations
2. Variation of vertex location on inner and outer broken line segments
3. Scaling of outer broken line segments
4. Angular variation of outer broken line segments

A specific geometric scoring diagram of the bird form, resulting from these topological transformations, defines a class of possible three-dimensional structures. For

instance, the bottom scoring pattern in Figure 5 is shown as a simulated video picture in Figure 6, and is shown as a photo of the actual three-dimensional folded object in Figure 7.

Both of the examples sited above, the ‘bird form’ and the ‘folded mosaic,’ have an associated geometric and topological transformation for achieving a specific three-dimensional shape. The following structure is determined solely by a topological transformation.

**OCTET-TRUSS**

The traditional ‘octet-truss’ is produced by a geometric generating system whose part rule predetermines it to be exclusively flat. I have created a number of topological transformations for this well-known structure which will map it to some desired surface shape. Figure 8 shows a sequence of domes of increasing curvature being created from one of these transformations. Each transformation preserves some geometric feature of the structure while distorting others, in order to achieve the required surface description.

**RESCH SYSTEM FOR HANDLING DISTORTION**

The impossibility of directly mapping a regular network onto a domed surface without distortion has been noted earlier. I have overcome this logical impossibility of building domes from identical pieces, by putting the required expansion and contraction in the folded crevices. The required variation of member length and facet dimension has been shifted to a variation in the angle between the modular plates. The procedure clearly isolates the necessity for variable length from the desire for identical modular components.

Therefore, it is possible to construct any variety of different domed surfaces from a repetition of identical modular plates by simply varying the dihedral angle between the plates. The mosaic fold shown in Figures 3 and 4, for instance, is composed of only two distinctly different triangles. A small collection of these two triangles will create a module which when repeated will form the mosaic of an entire structure.

It is easy to conceive of machines which would readily change this collection of plates by varying the fold angle between the plates rather than the dimensions of the plates themselves. In developing such an automatic manufacturing process for architectural structures, it has seemed wise to first develop experience at automating the production of models. Two automatic techniques have been explored.

First, hand scoring of the flat sheets to be folded has been replaced by numerically controlled scoring. This was achieved by modifying a flatbed plotter with the addition of a custom made scoring stylus and four pounds of dead weight to emboss a score line into a sheet of rigid vinyl. In exploring the sculptural and architectural possibilities of the ‘bird form,’ this technique proved invaluable, as every designed form had a unique scoring diagram.

Second, the automatic scoring procedure of scoring paper and vinyl sheets was extended to metal plates by a photo-chemical milling technique. Instead of pressure scoring, as in paper or vinyl, a metal sheet requires the removal of material along the line to be folded. Again a digitally controlled plotter was used to draw the score
lines. This artwork was transferred to an aluminum plate and the pattern chemically engraved. The sheet was then folded by hand. The ‘bird form’ on the cover of the “Communications of the ACM” was produced in this manner.

CONCLUSION

My work in the area of structure design, having been coupled with the computer as a medium of design and production, seems to suggest its possibility as a communications medium. The obstacles of achieving a facile relationship of people and things seems to inhere not so much in the structure of things themselves as the structure of our ideas and values. I believe from present experience that it is possible to reintroduce a ‘soft prototype’; to pay attention to the subtle variations of user needs; to conceive of objects as a continuously varying class of solutions to a continuously varying set of needs; and to use these needs as input to a transformation upon this topologically conceived object class such that it determines a specific set of instructions that will work within the variations made possible by automatic machines and process.

I believe that a large number of specific demands on a production process can result in an equally large number of individual objects, of a class of objects, at no substantial increase in total cost, if the system is so designed. This total concept I have called topological design.