The Development of a Computerized Form Generator for Space Frame Structures

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INTRODUCTION

Space frame structures date to the late 19th, early 20th centuries. Alexander Graham Bell is often credited for its invention but it was August Föple who first published a treatise on space frame structures in 1881 (Schueller, 1983). The first commercially available system, the Unistrutt system, was available in 1939 (Condit, 1961) followed quickly with the MERO system which was available in 1940 (Schueller, 1983). Since then many systems have been introduced and many advances have been accomplished in space frame technology, but the morphological realities of such systems has changed little. Architecture which utilizes space frame structural systems tends to be planar, cylindrical or spherical in form, but these are not the only morphologies possible. Pioneers in the use of space frame structures envisioned these structures as being able to be molded to any morphology. A grammar based geometric generator for space frame structures is in this area of study. The generator is used to match a space frame structure to a predetermined morphology. In this manner space frame structures are capable of many morphologies not previously attributed to them.

MORPHOLOGY OF SPACE FRAME SYSTEMS

Space frame structural systems are vector active systems (Engel, 1967); that is , a system which transfers applied loads through a series of axial members. A force enters the space frame system, typically at a nodal member, and is distributed amongst the axial members. Bending and shear forces are handled within the internal axial stresses of the members. The space frame structure acts as a network, where one piece is not easily distinguished from the next. The morphologic characteristics of space frame structural systems are based on this network. The characteristics of the individual members are distinct but the larger morphology has an identity of its own.

The nodal member of a space frame system is a determining factor of the system's morphology. The connection methodology of the node will determine the polyhedra possible with the system. Wachsmann wrote, "The joint module determines the position of every point off direct connection from the chosen system" (Wachsmann, 1961, p. 66). Each nodal member must be supported by strut members from translation in the three cardinal directions in order to maintain stability. This means that each node must have at least three non-coplanar axial member connected to it. The more axial members that can be accommodated at a any given node the greater number of morphological possibilities for the system (Gerrits, 1994).

In 1959, Konrad Wachsmann was commissioned by the U.S. Air Force to develop structures for very large airplane hangars. Wachsmann viewed the project as a problem in developing a building system which would permit every possible combination of geometry with standard, factory made units (Wachsmann, 1961). The system he developed was composed of a set of standardized linear members and a node which would allow up to twenty linear members to be connected to it at one time. Wachsmann provided the ability to build many different airplane hangars, as well as other building types, using this kit of parts. He demonstrated that more than just standard buildings could be designed using standard parts. Wilkinson claims that with this project Wachsmann brought "the science of industrialization to architecture" (Wilkinson, 1991, p.52). This was the beginning of one of the most imaginative periods for building with space frame structures.

Most buildings that use space frame structural systems tend to take their morphology from other structural systems. The most common type of structural system for space frame morphology to mimic is surface active structural systems (Engel, 1967). Surface active structural systems include domes, vaults, and shell structures. Space frame structural systems have also been designed to mimic beam, beam grid, cantilever, and portal frame systems. Engel classifies these systems as bulk active systems. The reason space frame structural systems mimic other systems is due in part to the analysis method used prior to computers.

Prior to the advent of readily accessible fast computers, the process of analyzing the structure was very complex. Space frame structural systems were virtually impossible to fully analyze due to their complexity. Therefore, engineers developed an approximate method through the use of analogous structural systems. If a space frame structure looked like a beam, it was analyzed as a beam structure. If a space frame structure looked like a plate, it was analyzed as a plate structure. For example, a horizontal space frame structure can be approximately analyzed as if it were a solid plate structure experiencing similar loading conditions as the space frame structure. It is assumed that the space frame system would behave similarly to the solid plate. This assumption is acceptable if the space frame is fairly dense and is made of stiff geometry (Schueller, 1983). Once the solid plate is analyzed, the forces in the space frame struts are approximated by determining which internal strut forces would produce bending and shear stresses similar to the solid plate. Analogous systems which have been developed include beam, arch, portal frame, beam grid, and shell structures.

A GRAMMAR BASED COMPUTER SYSTEM FOR THE DETERMINATION OF THE MORPHOLOGY

Architects and engineers have metaphorically compared the building arts to language. Peter Rice writes of making his structures legible (Rice, 1994). Liebeskind is quoted as stating that "the interpretation of past architecture is dependent on a structural reading" (Wojtowicz, 1986). Architecture, like language, is composed of elements and has structure which defines the relationship between the elements, and like language, the number of elements is limited. This limitation does not restrict the possibility of different architectural styles or different languages. It seems reasonable that this would be developed further. Prior to the modern movement architectural research relating to language was focused primarily on the elements, or vocabulary, of architecture. An example of this is the work of Durand, who composed a "dictionary" of architectural elements (Durand, 1802). Architects would combine selected elements for their individual projects (Wojtowicz, 1986). During and after the modern movement, some architectural researchers turned to grammar researchers in linguistics for inspiration.

There are two approaches to grammar research in linguistics which are currently being discussed in architectural research. The first type is generative grammar research. Generative grammars are rulebased and can be used to generate new sentences in a particular language. The second type is universal grammar research. Universal grammars describe the commonalties between all languages and identifies patterns in how languages may differ. The architectural research reported here is based on generative grammar research. One of the pioneers of generative grammar research in architecture is George Stiny, who referred to these grammars as shape grammars (Stiny, 1976). Stiny developed shape grammars through the examination of collected samples of architecture. Typically these samples consisted of several buildings from one architect or one architectural style or type. Stiny defined a shape grammar as consisting of an initial shape (I) and a set of rules (R) for manipulating the shapes (Stiny, 1979). He defines shapes as a finite arrangement of lines (Stiny, 1976), which leads to the rules being manipulations on a set of lines and the architectural design being a composition of lines. He has developed shape grammars for Chinese lattices (Stiny, 1977), Froebel's building gifts (Stiny, 1981) and Greek Cross Churches (Stiny, 1976).

One of the recent significant research developments in the area of generative grammars in architecture comes from one of Stiny's collaborators, William Mitchell. Mitchell kept the concept of the generative grammar as presented by Stiny but he differed from Stiny by changing the vocabulary of the grammar (Mitchell, 1990). In Stiny's shape grammars the vocabulary was defined by a set of lines. In Mitchell's work the vocabulary is defined from the set of architectural elements. This vocabulary can include such elements as columns, windows, pedestals and entablatures. Mitchell refers to these grammars as functional grammars. By using the architectural elements as the vocabulary for the grammar, Mitchell has begun to link the grammar research begun after the modern movement with the vocabulary research accomplished prior to the modern movement.

The grammar for the computer program developed for imaging space frame technology is based on the nodal geometry of the space frame system. The particular space frame nodal system investigated is the cuboctahedral, a twenty-six sided polyhedron (Figure 1), nodal space frame system. This system was first developed by Dr. Mengerinhausen in 1940 which later became known as the MERO space frame system. The nodal geometry defines the triangular faces and the tetrahedral units possible with the system (Figures 2 & 3). The triangular faces and the tetrahedral units are the vocabulary for the system. A grammar was then developed using this geometric information (Figure 4). In general the grammar defines a set of rules which define the how two tetrahedral space frame units may be connected, i.e., if a triangular face is unattached a new tetrahedral unit may be attached to the face following one of the rules.

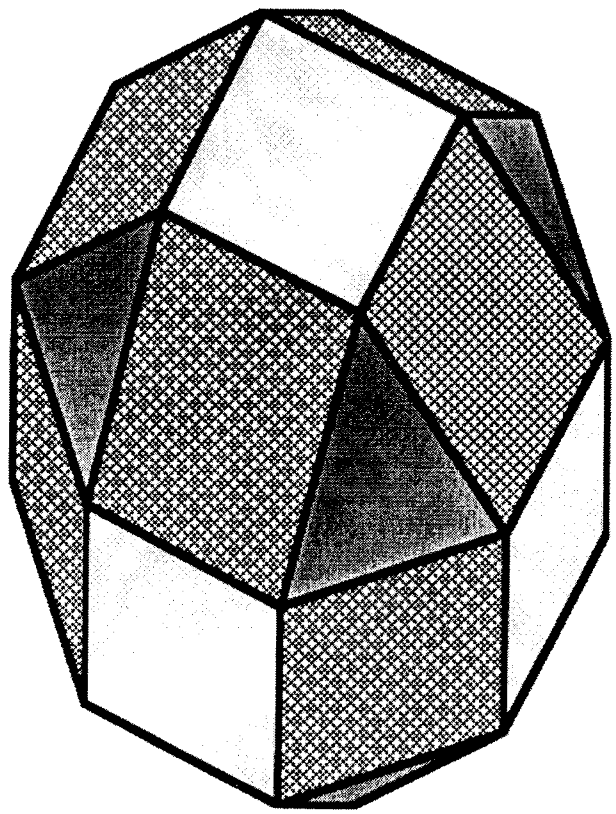

Figure 1. A Cuboctahedron

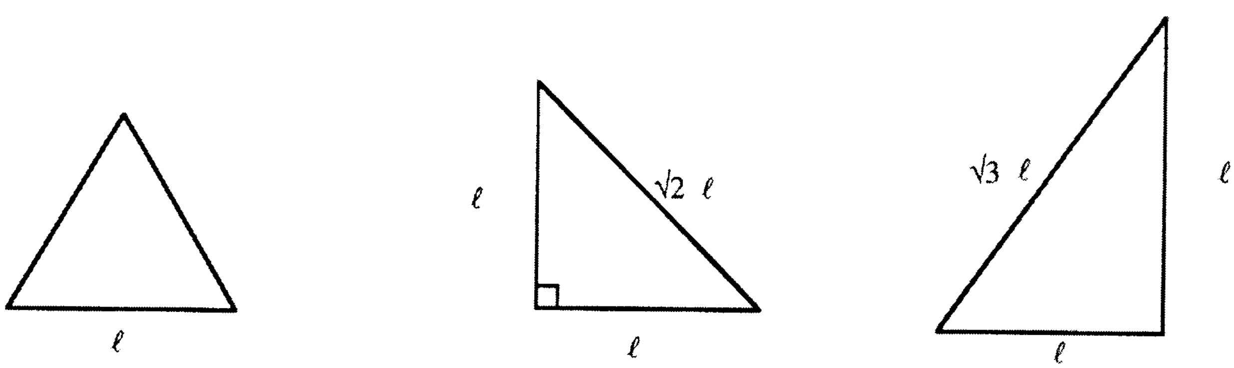

Figure 2. A partial set of triangular faces available using a cuboctahedral nodal space frame system.

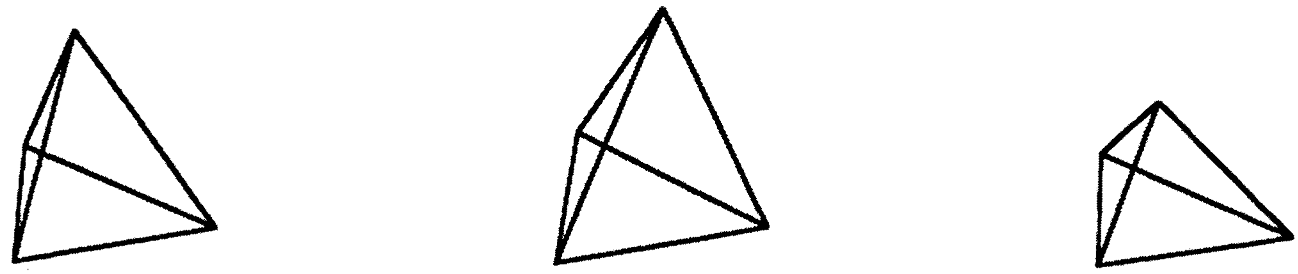

Figure 3. A partial set of tetrahedral units available using a cuboctahedral nodal space frame system.

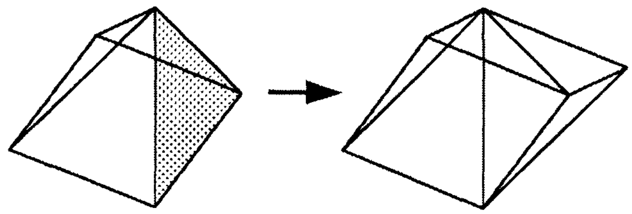

Figure 4. One grammar developed for a cuboctahedral space frame system.

he grammar is just the generating engine for the computer program. The program is also in need of a couple of other input constraints in order to be an effective design tool. The first is a boundary condition which will constrain the generation of tetrahedral units (Figure 5). Unlike earlier boundary constraints imposed by the limits of the structural analytic technique this boundary condition is imposed from the architectural side of the design process and has nothing to do with the structure's morphology. The final input required for the design tool is an initial tetrahedral unit which the grammar can act upon (Figure 5). The placement of the initial condition is of particular importance since it defines the orientation of the final morphology.

The flow of the design process using this computer program will begin once the architect determines what morphology the building should have. This morphology is translated into a set of boundary conditions which is inputted into the computer program. Next the architect will choose which tetrahedral unit is the initial condition is and where it is located within the boundary conditions. This is where the computer takes over and systematically fits a network of space frame tetrahedral units to the input conditions.

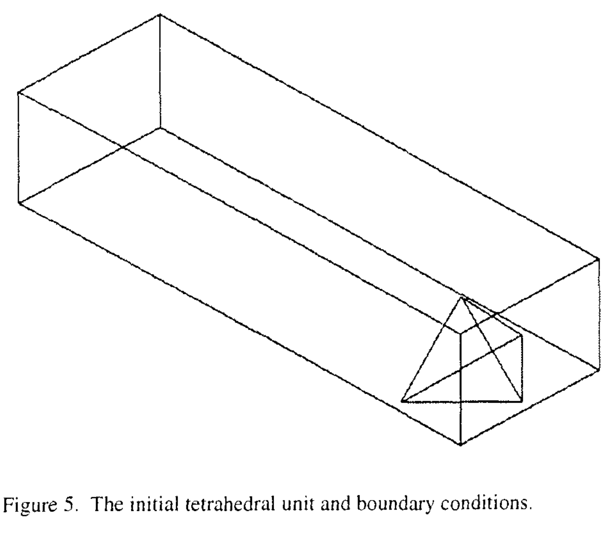

Figure 5. The initial tetrahedral unit and boundary conditions.

THE COMPUTER ALGORITHM

The computerized form generator was implemented into a computer program using the C programming language on a Apple Macintosh computer. This language and computer was chosen since a set of programs which could be used to produce the graphics images of the morphologies generated was already written.

The input files for the system consisted of a boundary definition, an initial tetrahedron, and grammar from which the form could be manipulated. The boundary defined the minimum and maximum values along a x-y plane and defining a minimum and maximum z value over different values of x and y. This allowed the development of planar morphologies but also allowed the development of segmented curvilinear and irregular morphologies. The initial tetrahedron was represented by its four triangular faces which are each defined by three nodes. An example of this representational syntax is that tetrahedron "1" is composed of triangular faces "A", "B", "C", and "D" and that triangular face "B" is an isosceles triangle whose vertices are defined by nodes "iii", "iv", and "viii". All tetrahedra in the system are represented in this manor. Finally the grammar was represented as a set of rules which define which tetrahedra can be added to any unattached triangular face.

Once the input data is entered into the program the reiterative form generator commences work. The first unattached triangular face is examined to see what type of triangle it is. The grammar is examined for the given triangular face type to determine which rules are applicable. If there is more than one rule is applicable for the given face type the computer randomly chooses one of them to apply to the triangular face. The rule informs the computer program of which new tetrahedron will be added to the existing face. Since three of the nodes of the new tetrahedron already exist the program only has to add one new node.

The new node is examined to determine if it is indeed a new node and whether it is inside the boundary. If it is not inside the boundary the program removes the new tetrahedron and applies another rule to the triangular face. Once again the new node is checked for uniqueness and its location relative to the boundary. This process continues until the new node is either inside the boundaries or no other rules apply to the given triangular face (Figure 6). The next available triangular face is then examined and the process continues until there is no unattached triangular faces exist which can have a rule fired upon it without produces a new node outside the boundary. When this process is finished the generated form is recorded as a set of nodes defined by their x, y, z coordinates and a set of axial members defined by their end nodes. Since this probability of recording the "best fit" for the given boundary on the first iteration of this algorithm is slight the algorithm is performed on the same input data numerous times until a "best fit" is produced. Once a final geometry is arrived at it can be exported to a computer graphics program for visual examination or to a finite element package for analysis. An example of a beam morphology generated by this algorithm is illustrated in Figure 7 and a planar morphology is illustrated in Figure 8.

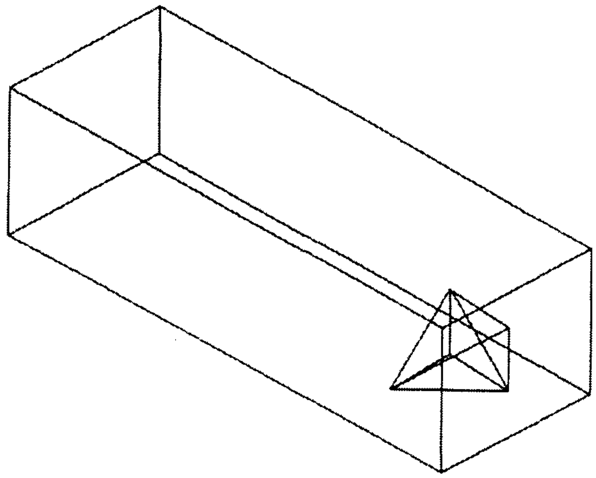

Figure 6. A random grammar being fired upon an unattached triangular face.

POTENTIAL USES FOR A FORM GENERATOR

The first potential use of a form generator is in the research into structural morphology. This was one of the primary purposes of this research was to provide a tool which could be used to investigate different morphologies, and possibly determine which morphologies are appropriate with space frame structures and which are not. There are many different types of space frame nodal geometries which each would have its own particular morphology, or morphologies which there are particularly inept at achieving. Through a comprehensive study of these systems, using a form generator, on could determine when it is appropriate for one system to be used and when it would be appropriate to use another.

A form generator could be used in practice as a design tool which could help to translate an architectural design into a structural system. Form generation by architects is done by many different methods, some digital and some analogue. Once a form is generated it could be imputed into the grammar based form generator to determine a space frame structural system which would be appropriate for the given boundary conditions. This process could be a best fit process using several different space frame nodal geometries. Once the best geometry is generated it could be given to the engineer

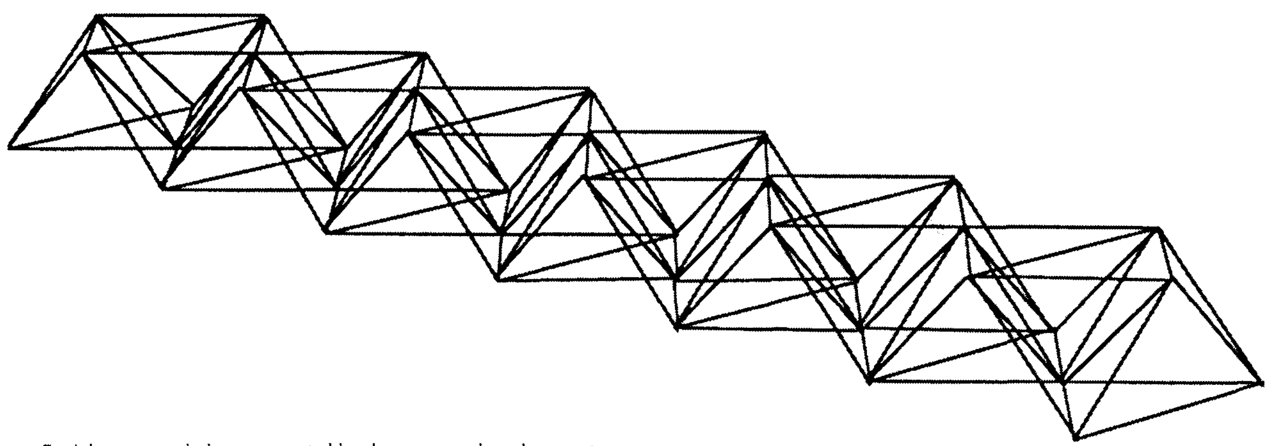

Figure 7. A beam morphology generated by the grammar based computer program.

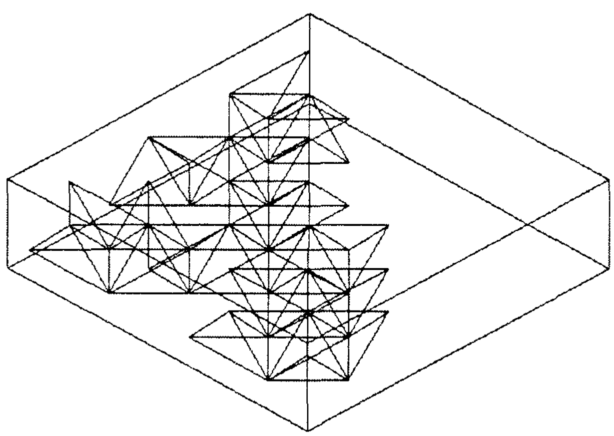

Figure 8. A planar morphology generated by the grammar based computer program.

or as a design tool. What is known is that the use of grammars as the basis of a form generator for space frame structures is an appropriate methodology. They have been successfully defined and have been successfully implemented into a computer system. They are able to generate different morphologies based on the inherent nodal geometry of the structural system. Mitchell was correct when he hypothesized that an appropriate determinate of an architectural design is its structure (Mitchell, 1990).

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