Computer Simulation and Visualization of Geometrically Changing Structures

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Abstract

The design of building structures that change shape and form to adapt to different functions or weather conditions requires the application of innovative building technologies, as well as the invention of a new architectural morphology. This morphology is directly related to the kinematic conception of the structure. A computer simulation of the motion of the structure and the display of the structure as an animation of moving parts can identify problems in its initial geometric and kinematic conception. It can also assess the effect of the changing geometry of the structure on space definition, building morphology, and functionality.

1 Introduction

In the last 20 years there has been an increased interest in building structures that change shape and form to adapt to different functional or weather conditions. These are usually structures that include moving parts, consisting of "rigid" members connected by movable joints, which allow for the geometric expansion of the structure in space. Deployable structures that can be transformed from a "closed compact configuration to a predetermined expanded form in which they are stable and can carry loads" and which find applications in temporary structures and aerospace industries, also belong to the same group of structures (Gantes 91).

Structures that change shape and form to adapt to different functions and weather conditions have an obvious positive impact on the economy of environmental resources. Deployable structures, that can be moved from a place to another, can also offer an environmental alternative to massive building structures since they usually do not require heavy foundations, minimize the overall workforce and the total erection energy needed, and are re-usable and adaptable.

Despite the advantages and promising applications of such structures, they have not yet been addressed as a distinct building class, mainly because of the lack of standardized procedures in their engineering design and analysis. From the standpoint of architectural morphology and typology however, they certainly define a distinct category of structures that offers unlimited possibilities for formal expression and functionality.

An early phase in the design process of any structure consists of the development of a geometric concept, based on requirements set by programmatic needs and specific site conditions. In this particular case of structures kinematic and geometric conceptions are directly and uniquely related, and should therefore be addressed together at the very beginning of the design process. Furthermore, since this concept of structure may allude to an architectural expression we have no prior experience of, its kinetic conception may as well play a significant role in setting standards for a new morphology and a new building typology. It is therefore imperative that an initial study of such structures addresses form and space development as a function of motion.

In addition, a characteristic feature in the morphology of these structures is that they involve a complex 3D geometry that is sometimes hard to visualize and represent. A computer simulation and visualization procedure is thus recommended as the most appropriate tool for the early exploration of their kinematic performance and morphology.

In the following sections a brief description of the methods that allow structures to move is presented first. Next, the stages in the computer visualization of geometrically changing structures are identified and issues of critical importance in this process are presented. Software requirements and student projects that display the application of the suggested procedure are also presented.

2 Kinematic Conception of a Structure and Architectural Design Features

The method that allows a structure to move plays a crucial role in the conception, architectural expression and overall performance of the structure. Folding of building parts, or bringing the entire structure into a compact configuration is usually the result of the application of mechanism-design principles in building construction. Scissor units, sliding building parts including telescopic parts, and folding umbrella principles are just some examples of mechanisms that can be utilized in the conception and design of geometrically changing buildings.

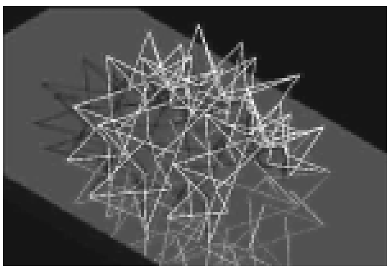

Figure 1. Arched scissor structure (student design).

In most cases of geometrically changing structures the deployment method is based on the design of movable units that can be attached to each other to form 2D or 3D moving assemblies. A typical example is the scissor unit, which can be described as an assembly of straight rods of equal length connected by pivots in the middle, or at a lower position, and at the ends. The geometry of the scissor unit, and the way scissor units are linked to each other to build an assembly determine whether the structure will expand in one direction only or in two directions. Linear frames and flat or curved movable space frames can be developed in this manner (Pinero 62; Hoberman 90). Examples of curved movable space frames are shown in Figures 1 and 2.

Assemblies of basic movable units can be applied to various types of geometrically changing structures. They can be used for the spatial expansion of retractable structures that have one free end and one end permanently attached to another building part or the ground. An example is the design for the cover of a swimming pool in Seville by F. Escrig (Escrig et al 1996).

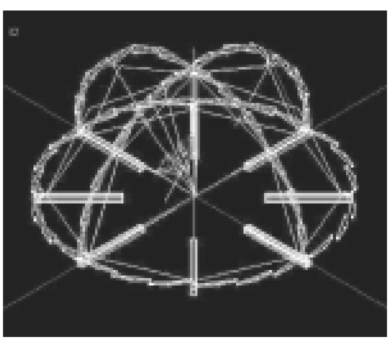

Figure 2. Spherical scissor structure (C. Hoberman design).

Assemblies of movable units usually form 2D trusses or 3D meshes which define the space of the structure in its various configurations but very often provide minimal enclosure and require additional covering for rainwater protection and controlled solar exposure and heat gains.

Combinations of fully functional deployable units, such as umbrellas, can be used to cover large open spaces. The pattern of the motion of individual units is related to the desired level of enclosure and solar exposure at each configuration (Figure 3). In some applications of the concept, such as in the Gartenrestaurant in Bauschanzi, Zurich, designed by S. Calatrava, all units open simultaneously, in others as in a student project illustrated below, that is based on the umbrella unit designed by Otto, each unit needs to follow a different pattern of deployment to avoid collision of parts with those of adjacent units (Figure 4). A potential advantage of the unit method is that by changing the geometry of the unit, a structure of a different morphology may be achieved.

A different method that allows for the redefinition of the enclosure of a building and which does not require the addition of any covering consists of sliding, or rotating entire building surfaces against each other. This is the main method employed in the design and construction of retractable domes and roofs in general.

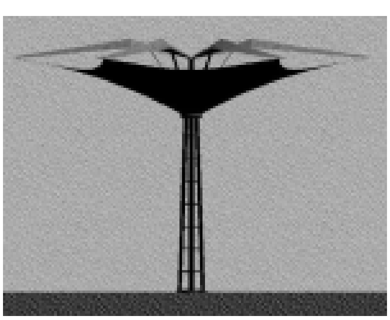

Figure 3. Umbrella unit designed by F. Otto.

A similar method that addresses permanent structures and does not require the addition of covering is particularly related to the kinematic conception of space-defining elements, which can be relocated and which acquire a different spatial geometrical and functional definition in their new position. The vertical wall in Calatrava's design of the aluminum doors on the Erenstings warehouse, which lift to become an undulating shading canopy in its new position is a typical example (Tischhauser 1992).

Apparently, the kinematic and overall geometric conception of the structure is directly related to space definition and the level of space enclosure in each functional configuration. Space enclosure in particular determines the relationship between the exterior and the interior of the structure, the amount of solar exposure, the depth of shadows, rainwater protection and air movement through the structure, all of which have an impact on design quality and performance.

New methods or mechanisms, for changing the geometric configuration of surfaces or structures are possible in the near future, due to innovations in structural materials. Eventually these methods will affect the kinematic conception, space definition and morphology of geometrically changing structures.

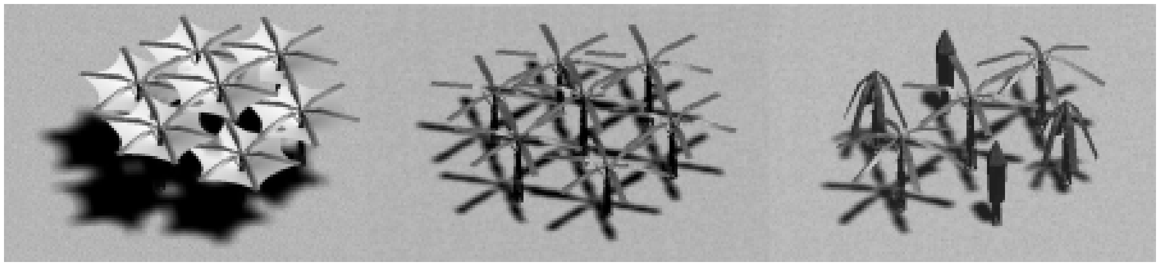

Figure 4. Multi-unit structure: Pattern of closing and opening umbrella units to avoid collision of parts.

3 Computer Simulations and Visualization

Since the kinematic conception of a structure imposes constraints on what can be realized and determines the form of the structure, a computer visualization procedure is recommended for a preliminary investigation of its kinematic performance and geometry in its functional configurations. The following stages may be involved:

3.1 Motion simulation and animation of the basic movable unit

This process applies to structures whose motion depends on the action of movable units. The same process can be applied to structures that behave entirely as one single mechanism.

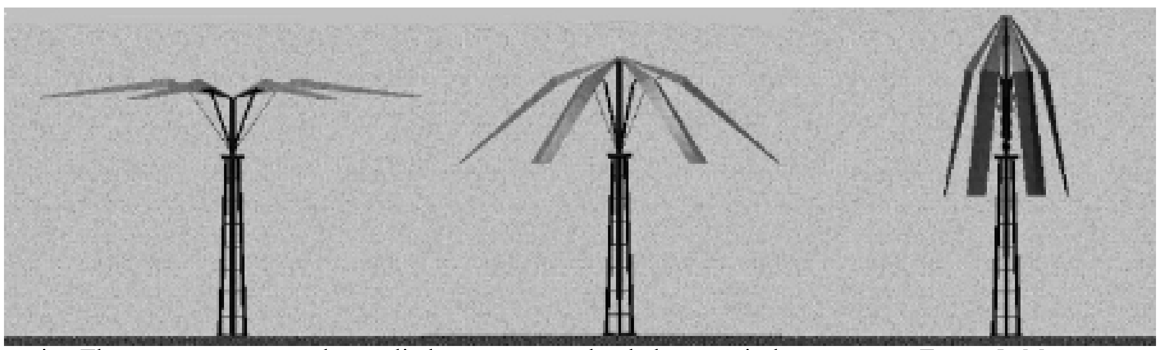

Figure 5. Motion simulation of the umbrella movable unit.

The objective of this stage is to verify and evaluate the path of the moving parts, and detect interferences between members.

A basic understanding of mechanism design is required, as well as the use of a software that (a) allows for an accurate and precise graphic representation of the geometry of all members in a 3D environment, (b) provides a physically accurate simulation of mechanisms, and (c) displays the results of the motion simulation as an animation showing the motion of the system (Figure 5).

More specifically, the first task in this process is to develop the 3D geometry of the parts and their joints, and to define the movable parts, the way they are attached to each other and the way they move relative to each other. The development of additional kinematic diagrams for the analysis of the motion of the members of the structure may be necessary. Respectively, the software should allow for advanced 3D modeling, including complex surface developments and Boolean operations, and the application of motion constraints to the members using graphical joint definitions for motion types such as: hinge, slider, screw, etc.

Viewing the results as an animation showing the motion of the system will help in detecting member collisions and overall errors in the conception.

3.2 Visual simulation of the motion of the structure

This stage involves the display of the model of the entire building structure as an animation of moving parts. The objective is to study the effect of the changing geometry of the structure on space definition, building morphology, and functionality.

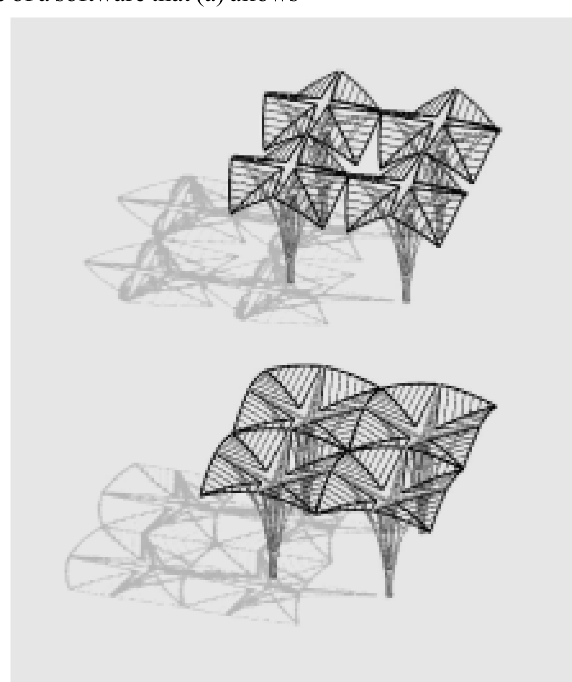

Figure 6. Animation of a multi-unit structure designed by S. Calatrava.

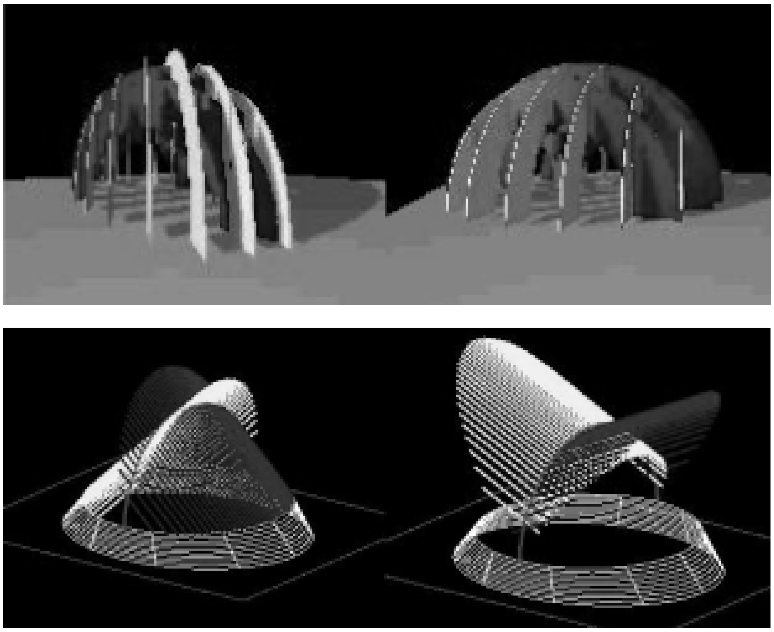

Figure 7. Examples of animation projects inspired by Origami art and a S. Calatrava design. Different animation techniques have been applied.

The motion simulation of all the components of the structure, following the procedures described in the previous stage, and their simultaneous animation may be cumbersome or impossible. A visual simulation of the motion of the entire structure is more feasible, especially if the structure is an assembly of movable units, and if the efficiency of the unit has already been verified. This part of the study also requires that motion paths or equations for the motion of individual parts or units have already been derived.

In general this stage requires an understanding of the motion of all components of the structure and software with advanced 3D modeling and rendering capabilities that allows for the simultaneous visual simulation and animation of the motion of design elements that perform identical or different types of motion. The animation of a camera view along a predetermined path, which will display the view of an observer while the structure is moving, is also a requirement. The 3D models of movable unit(s), which have been developed in the first stage of this study, should be used for the geometric description of the entire structure.

For the visual simulation of the motion of the entire structure the software should offer various techniques for animation, and the possibility of combining different techniques. Sometimes one single technique is not adequate, but if combined with other techniques may allow for the visual simulation of very complex structures. For example, frame animation requires that the designer knows already the position in space of basic components after motion has been applied. This implies that the motion of parts has already been studied in the first stage with a physically accurate motion simulation, or with the help of kinematic diagrams and physical models. The simultaneous display of animations of all components in a structure can detect interferences and collisions between the members and individual components.

In building structures with complex assemblies of moving parts where each part performs a different type of motion, the application of a technique that allows for the attachment of members in a hierarchical manner, (that is by stimulating the motion of one part of the assembly, any parts below it in the hierarchy will be also moved), may provide a solution for structures that include components that consist of parts attached one to the other (Figures 6, 7). In addition, parametric animation techniques allow the user to specify the geometric position and orientation of parts after the motion as a function of time. This requires that the equations of motion have already been derived. Giving values to variables of the equation will allow for the study of variations in the motion of the structure. An example is the visual simulation of the motion of the Kuwait Pavilion by Calatrava in which the use of parametric equations allows for different rhythmic patterns in the motion of the finger looking members.

An initial assessment of the response of the form and kinematic conception of the structure to different functions and climatic conditions can be conducted at this stage. Studies that can assess the functionality and architectural expression of the structure may include (a) the light/shadow pattern in the interior or exterior of the structure at different times throughout the year (b) the rainwater protection at different geometric configurations, and (c) the overall morphology of the structure. In the case of deployable structures the efficiency of the deployment procedure can also be studied at this stage.

Finally, the animation of a camera view along the path of a moving observer can provide some input on what the observer sees as he approaches, moves through and out of the structure in its functional configurations, or while the structure moves (Figure 8).

Computer visualization procedures, such as the ones described previously for a preliminary investigation of the form and kinematics behavior of geometrically changing structures, have been included in the content of an advanced CAD course taught by the author. All illustrations in this paper are produced by students in the class and attest to the effectiveness of the recommended visualization procedures.

4 Conclusions

Geometrically changing structures open unprecedented worlds of possibilities for architects and engineers, and respond to the continuously increasing demand for structures that reduce the environmental impact. Computer simulation and visualization offer tools for the exploration of their kinematic performance and the study of their space and form. Software requirements have been set in order to obtain highly accurate geometrically and kinematically animations that have been used in the study and visualization of existing and new structures.

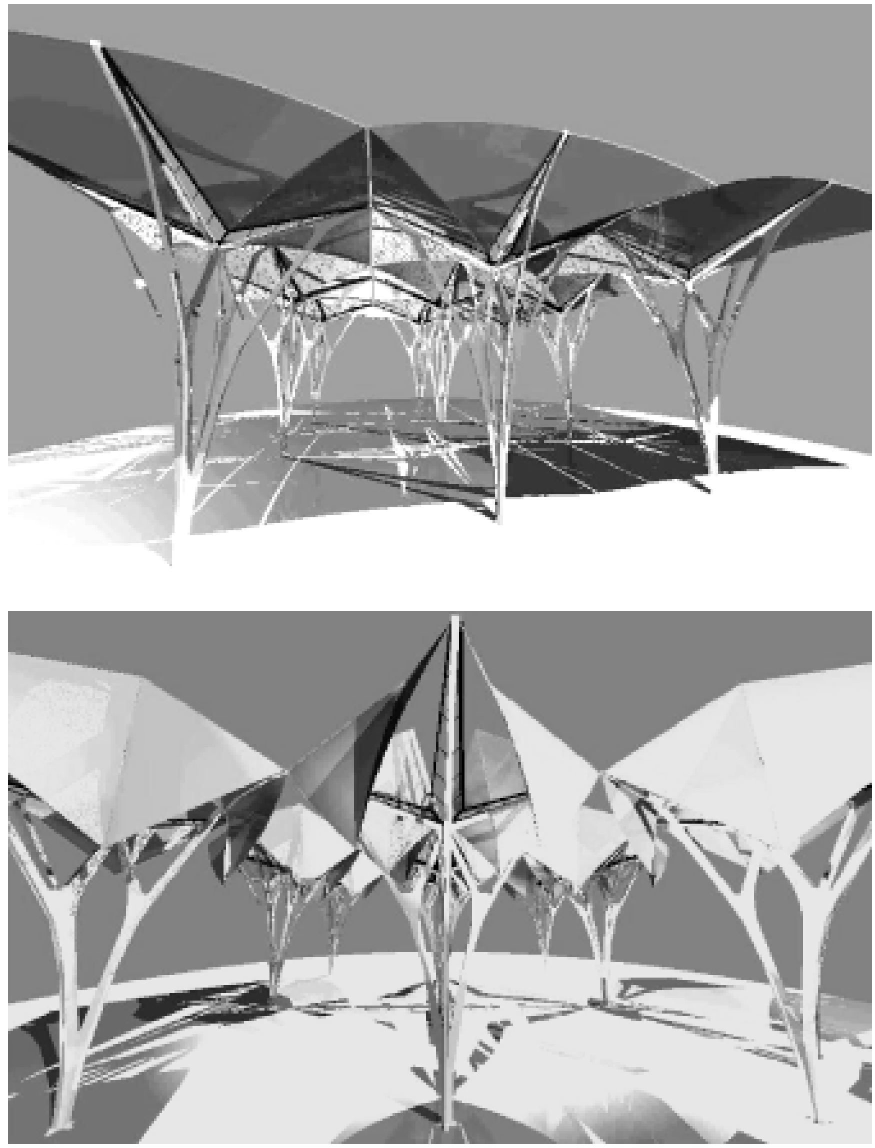

Figure 8. Animation.

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