Transformable Architecture Inspired by the Origami Art: Computer Visualization as a Tool for Form Exploration

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Abstract

Membrane packaging has been the main feature of the earliest prototypes of transformable architecture. Similar concepts of spatial transformation are encountered in the origami art where a planar paper surface, after folding, transforms to a 3-dimentional object. The geometric configuration of creases on a sheet of paper before folding, as well as the topological properties of 3D origami paper models, have been recently addressed, and can be used as a guide for the design of new forms. Because membranes in general can be considered surfaces of minimal thickness, principles of the origami art and math can find applications in the conception and design of transformable membrane structures for architecture. This paper discusses how computer visualization can be used to explore the potential application of ideas borrowed from the origami art in the conceptual design of transformable structures. A two-case study that shows how origami math is integrated in the computer visualization of a potential architectural application is included. The same study also shows that animated simulations of the transformation process during folding can identify problems in the initial geometric conception of an origami type structure, and can be used for further morphological explorations.

1 Transformable Architecture: Conceptual Prototypes

Transformable structures can be defined as structures that are "capable of executing large configuration changes in an autonomous manner. The configuration of such structures changes between a compact, packaged state, and a large, deployed state" (Pelegrino 1999).

This definition does not differentiate between product design and application for human habitation. In its most general expression, it can apply to any natural form that can change shape to adapt to a new condition. There are many examples of transformable structures in nature, and many apparent reasons for their evolution. Whether one observes the motion of a worm, a wing of an insect, or a petal of a flower, any transformation in their geometric configuration is a vital part of their existence. The understanding of the spatial configuration of transformations and mechanisms that allows natural forms to change has led the human analytic thought to the creation of other transformable forms that serve various domains (Vincent 1999; Kappraff 1990). In most cases, the invention of such structures is driven primarily by a fundamental concept of geometric change, even though the mechanism of the transformation is very often significantly different from that used in nature.

Membrane folding is a fairly common transformation process that allows plants to assume more than one spatial configuration. Membrane folding is also encountered in architecture as a method of changing space definition and enclosure. Indeed, a search for the historical origins of transformable architecture reveals that close packing of membranes was probably the oldest form of portable home that could be folded and carried on the back of a camel. The covering of big market places was another significant historic example that involved membrane folding.

Membranes, including *stressed-skin* structures, placed in the context of architectural applications, can be used as surface coverings or space definition elements, and often perform as the main structural component. Because they are thin, membranes can be bent easily. But they are relatively difficult to stretch. In nature, the hard exoskeleton of a beetle or a lobster acts the same way. Hence, in studying the packaging of membranes, it is normal to model them, as Pelegrino suggests, as “in-extensional plates” of zero thickness. A characteristic of membranes, from a purely geometric point of view, is that they are continuous surfaces and in some configurations can be considered as planar forms, which, after a certain transformation process, acquire a 3D configuration.

Planar form folding is an integral part of artistic practices that matured within several cultural traditions, the origami being the most prominent. Origami art, which in contemporary terminology refers to the Japanese art of folding paper, has incorporated a very sophisticated and subtle understanding and application of the geometric transformations that allow a flat surface to transform to a 3D structure. The study of the geometric and topological properties of origami folding has challenged several mathematicians who have formulated folding principles and theorems.

In this regard, when studying membrane folding and packaging, one can take advantage of recent developments in origami art and math. A logical deduction that derives from this conviction is that, although nature remains the most broad source of inspiration for the conceptual design of any transformable structure, the understanding of origami art and math alone can offer a vast world of opportunities for transformable architecture. A methodology based on this assumption has been developed for the study of the conceptual design of structures that are based on the origami art.

In the following sections, a brief reference to the origami history is made first. Next the geometric characteristics, properties, and main principles that apply to the folding of planar surfaces are presented. Finally, a step-by-step computer visualization methodology of transformable structures that can be used in the exploration of origami based architectural conceptions is discussed, and two examples of the application of this methodology are presented.

2 On Origami Art: Origins and Mathematical Properties

The term origami, coined from. the words *oru* (to fold) and *kami* (paper), is first mentioned during the 4th century A.D in Japan. It referred to square and rectangular pieces of paper, folded into symbolic representations of the spirit of God, and hung at the Kotai Jingu (Grand Imperial Shrines) of Ise as objects of worship. During the 11th century A.D. folded paper came to be used for certificates that accompanied valued objects such as swords or gifts presented to others. At this time, the term "origami" referred to the documents, whereas the term *origami tsuki*, "accompanied by origami", meant that a gift was accompanied by a certificate. This certificate had the same meaning as the word *diploma*, which in ancient Greek also means "a letter folded in two." The use of the term origami for recreational paper folding did not appear until the end of the nineteenth century or the beginning of the twentieth. Before this time, paper folding for play was known by a variety of names, including *orikata, orisue, orimono, and tatamgami*.

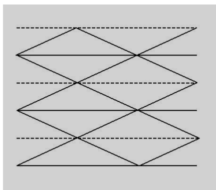
In the 1930s, the art of origami expanded beyond traditional designs. At the same time, the development of instructions, based on line systems and arrows, made origami available to the west as a new creative tool. After this time, experimentation with new ideas went beyond figural origami to gradually include more abstract forms, among them various types of closed and open surface developments (Anderson 2002), which can also find applications in transformable architecture.

2.1 Geometric features

The increased interest in new and challenging origami forms eventually led to the investigation of the mathematical properties of paper folding. A close observation of the planar geometry of origami models, and a review of the theorems that have already been formulated, are summarized in the following paragraphs.

After unfolding an origami 3D paper model until it reaches a flat configuration, a clearly defined crease pattern is formed. The crease pattern consists of two systems of lines, which, in the 3D configuration, represent hills and valleys. These lines are usually indicated on paper with two different line-styles. When these two systems of lines intersect, they form self-similar surface elements, to be called here tiles. The shape of the tiles that occur in this manner is polygonal with or without side regularity. In the origami formation of Figure 1.a, all tiles are triangular in shape, whereas in the formation of Figure 1.b,, different sizes of tiles of trapezoidal shape are created.

Another geometric characteristic of origami crease patterns is that they display several types of symmetric organizations. The formation in Figure 1.a presents a bi-axial symmetric and repetitive organization of tiles. The formation of Figure 1.b is characterized by a rotational symmetry around a point.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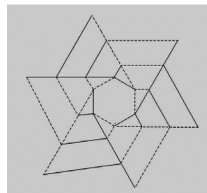
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Figure 1: Origami crease patterns

Origami crease patterns often belong to the category called patterns of *unlimited growth*. Both formations we just discussed can be described as patterns of unlimited growth. In Figure 1.a growth results from the repetition of identical tiles, whereas in Figure 1.b growth results from a spiral development of self-similar rows of tiles. Seen from a different point of view, the pattern in Figure 1.a is invariable under n-mirroring processes, whereas the pattern in Figure 1.b is invariable under n fold rotations about the center.

2.2 Topological properties

In addition to the geometric features and variations in origami crease patterns, several theorems and principles that determine what can, or cannot, be done by paper folding have been formulated (Anderson 2002; Pelegrino 1999). These are:

A general topological condition that any pattern of creases must fulfill requires that the number of creases originating at a vertex be always even. A different expression of the same condition is described in the following theorem: Every flat-foldable crease pattern is two-colorable. Both schemes in Figures 1.a. and 1.b. fulfill this requirement.

A second condition requires that when four creases meet at a common point, the difference between two adjacent angles has to be equal to the difference between the remaining two angles. This condition is usually referred to as the Hushimi theorem. Both schemes in Figures 1.a and 1.b satisfy this condition as well.

Finally, a third condition, known as the Kawasaki theorem, requires that the angles a_1, a_2, a_3, ..., a_{2n}, surrounding a single vertex in a flat origami crease pattern satisfy the following requirement :

$$a_1 + a_3 + a_5 + ... + a_{2n-1} = 180 \text{ degrees}$$
and
$$a_2 + a_4 + a_6 + ... + a_{2n} = 180 \text{ degrees}$$

In simple terms, this relationship between angles surrounding a vertex is to prevent gaps between creases meeting at the same vertex when folding the paper.

These conditions set the necessary geometric and topological framework within which existing origami patterns can be understood or new ones can be created. These same principles and conditions allow us, once a basic geometric configuration is placed on a 2D surface, to explore variations that can lead to 3D formations.

3 Kinematics and Computer Visualization of Origami type Structures

A characteristic feature of origami-type structures is that they always involve more than one geometric configuration. These configurations are the result of a complex kinematic process, and as such they are difficult to represent and visualize. Obviously, the kinematic behavior of an origami structure is an integral part of its original geometric conception, and it should be addressed early on during the form exploration process.

A close observation and study of the kinematics of origami-type structures reveals that each one of the tiles, which occur from the intersection of crease lines, performs as a mechanism. Respectively, the entire structure can be described as an assembly of moving parts. In this context it becomes obvious that any changes in the features of the crease pattern will change the relationship between tiles, the kinematics of the structure, and the interim and final geometric configurations of the structure.

An observation of the kinematics of different origami-type structures also shows that at least two different methods for folding or unfolding origami structures are possible: a) the model unfolds in a sequential fashion, that is, distinct steps must be followed and each new step starts when the motion of the previous has been completed; and b) the structure deploys synchronously. The latter means that all tiles move at the same time, and the motion of one affects the motion of all other tiles adjacent to it.

For the study of origami-type structures, a computer simulation and visualization method that takes into account the origami kinematics is proposed. A first step in the process is to create a virtual sheet of paper on which all crease lines are drawn, and to examine whether the 2D crease pattern fulfills the requirements set by the origami theorems.

The second step consists of defining each tile that occurs from the intersection of crease lines, as a separate surface in a 3D environment. A third step consists of analyzing the kinematics of individual tiles, including the method of connection with adjacent tiles, axis, point of rotation or translation, degrees of freedom, max. or min. angles of rotation, etc. Determining the degrees of freedom of each tile is the most challenging part of this process. At this stage, the application of the topological conditions will be used in reducing the degrees of freedom and facilitate the kinematic simulation of individual tiles. In cases of origami patterns of unlimited growth, a minimum number of tiles that are required for studying the kinematics of the model, must determined prior to the simulation.

To perform this analysis, kinematic simulation software that can be interfaced with commercial CAD packages and which permits the application of motion constraints to the members using graphical joint definitions for all motion types was used. The same software application allows for a) a physically accurate kinematic simulation and b) the animation of the results of the kinematics simulation in a 3D environment. Viewing the results of the kinematic simulation, as an animation that shows the motion of individual tiles, helps in detecting errors in the original conception, and aides experimentation with the tiling parameters.

In order to evaluate the efficiency of the origami model for a specific architectural application, the display of the model of the entire structure as an animation of moving parts is required. This makes possible the study of the effect of parameter variations on space definition, enclosure, as well as the study of the overall morphology. For the kinematic simulation of the entire origami structure, software that offers animation techniques that allow the hierarchical attachment of members (that is, by stimulating the motion of one part of the assembly, any parts below it in the hierarchy are also moved) was used. An initial assessment of the response of the structure to its functional requirements can be conducted at this stage.

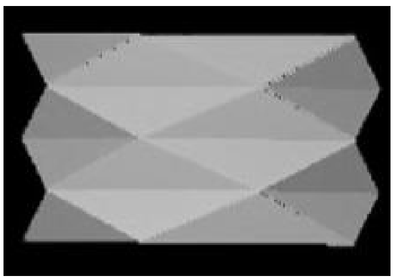
4 Morphological Exploration of 0rigami Architecture

The method described in the previous section has been used for the morphological exploration of architectural structures based on origami concepts. Two different applications of architectural membrane folding have been examined and are described below. Both applications display a tubular morphology. Two different origami crease patterns have been chosen, and virtual models have been generated. The development of the virtual folding in each instance is also described.

4.1 Transformable Vault

Tubular structures in nature, like worms, become short and fat by contracting their longitudinal muscles; contracting their circumferential muscles makes them become long and thin. Similar concepts of geometric expansion can be generated with the use of origami folding. A vaulted structure that can adjust in length and section to fit to an aperture is a possible application of this concept in architecture (Sedlak 1973).

This study has used as a prototype of an existing origami crease pattern. In the diagrammatic description of the pattern, as shown in Figure 2, valleys and hills are indicated with solid and dashed lines, respectively. An analysis of the geometric features of the diagram indicates that a) the vault, as it appears on the scheme, is composed entirely of a sequence of identical isosceles triangles arranged in a parallel configuration, b) the angle of the isosceles triangles can vary between 0 and 180 degrees, c) the angle defined by two consecutive valley and hill lines is bisected by a hill or valley line, respectively, d) the curvature is obtained by folding down the two dotted families of lines and by folding up the solid family of lines and, e) The convex foldings are created in between the diagonal creases, whereas the creases that are perpendicular to the axis of the cylindrical vault produce concave folding or creases.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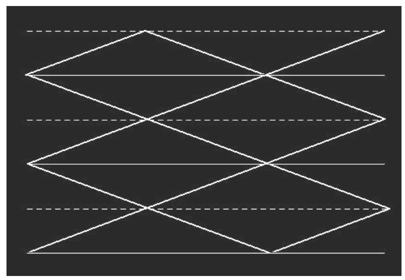
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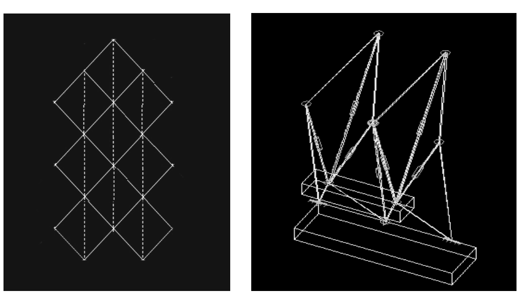
Figure 2: Crease pattern of a vaulted structure

The above constructions were repeated in a virtual sheet of paper. Triangular surfaces that correspond to the tiles in the pattern were built in a 3D environment. A cluster of 16 tiles, four rows of four, as shown in Figure 3, was selected for the kinematic analysis. Once the motion parameters were defined, changes in the angles of the triangular tiles and their total number were possible. This allowed experimentation with different expansion methods and various morphologies. The proper selection of the angle of the basic triangular unit allowed the structure to acquire a closed tubular configuration of hexagonal section. In addition, the kinematic simulation and animation indicated that the structure could expand in two different ways: a) along the longitudinal axis of the tubular structure, as it was anticipated, and b) along the sectional axis, which was not considered as an option before the kinematic simulation (Figure 4). A visual simulation of a structure composed of several basic modules was also generated (Figure 5). The latter allowed us to visualize vaulted structures of various curvatures and depths.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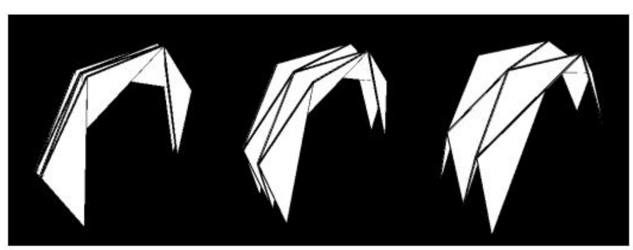
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Figure 3: Kinematic analysis simulations of a 16 tile structure
Figure 4: Animated motion of a 16 tile vaulted structure

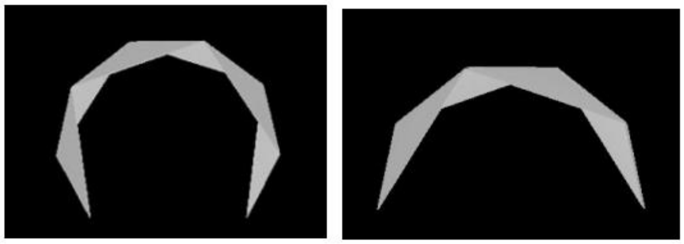
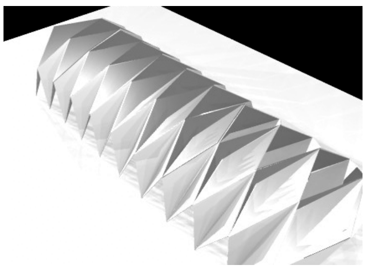


Figure 5: Expansion of the structure along the two main axis



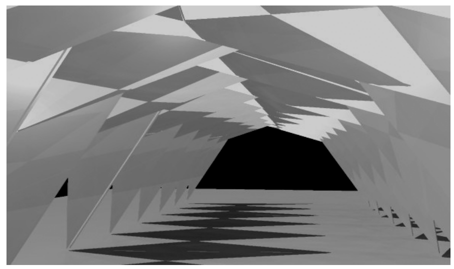


Figure 6: Visual Simulation of a vaulted structure **Figure 7:** View of the interior of the vaulted structure

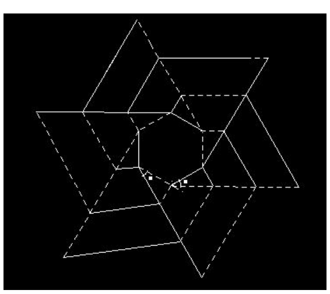
4.2 Transformable Canopy

Several plants, and most often flower buds, consist of a thin continuous membrane and present two distinct configurations during their life cycle: In one, usually at an early stage in their lives, or during the first part of a diurnal cycle, the folded membrane forms a sort of a cylindrical hub. During a more advanced stage of their lives, or during the other part of the diurnal cycle, the membrane unfolds to form an almost flat surface perpendicular to the original direction of the folded membrane.

This concept was used as a prototype for a preliminary study of a space covering system. More specifically, the idea was to develop a modular structure composed of bud looking units. In the unfolded configuration, units form a continuous overhead surface to provide space covering for shading or rain protection.

The mathematical properties of a membrane packaging scheme with features similar to the unfolding of flower buds was invented in the early 1960's.

A diagrammatic description of this membrane packaging scheme is shown in Figure 8. Valleys and hills in the scheme are indicated with solid and dashed lines, respectively. The angular relationships that allow the structure to fold in a direction perpendicular to its original flat configuration is shown in Figure 9 (Pelegrino 1999). From the application of basic trigonometric and geometric relationships, it can be easily proven that, when the membrane in the compact configuration has the shape of a regular prismatic form, then the angle *a* that allows for a fully wrapped configuration is directly related to the value of the angle of the polygonal base of the prismatic hub.



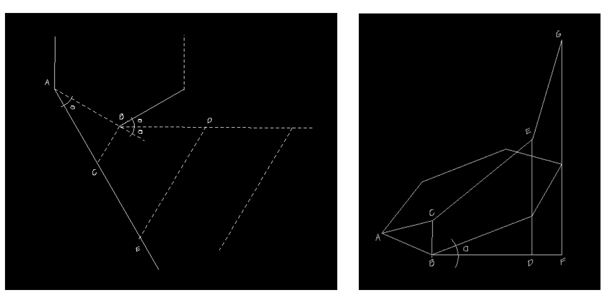


Figure 8: Spiral crease pattern **Figure 9:** Angular relationships in the expanded and folded configuration

Previous research has provided a significant topological requirement specific to this type of folding (Pelegrino 1999). According to it, when four creases meet at a common point, there are at least four folds; three have one sign, and the fourth has the opposite sign.

Both geometric and topological requirements were taken into account for the morphological exploration of a space-covering modular unit. At first a virtual membrane of a polygonal shape was created. Then, based on the pattern of crease lines on the paper, a system of planar tiles, linked to each other with hinges, was built. The topological requirements according to which only three folds can have a positive sign and one a negative, were taken into account for setting the parameters of the kinematic simulation of the structure. The kinematic simulation has allowed us to study intermediate positions and boundary configurations. It also has allowed us to study polygonal prismatic hubs of octagonal, decagonal or other n-sided bases, without the need to build tedious models. Spiral systems of various numbers of tiles were also studied. This allowed us to experiment with various morphologies.

The final design of the structure occurred while experimenting with an angle *a* that is different than the one that derives from the membrane packaging geometry. This angle was used for defining the pattern of spiral line constructions that emanate from a hexagonal center. When this different angle was used for wrapping the surface around the hexagonal core, the kinematic analysis indicated that the membrane could not fold. After this, by cutting lines on the virtual sheet of paper, following the valley pattern all the way up to the central polygon, a new concept of membrane folding was discovered. According to this, the n-polygonal membrane in its flat configuration consists of n smaller membranes that look like flower petals and which fold in a symmetric spiral manner around the central axis of the polygon until a prismatic hub is formed. (Figures 10). The prismatic hub looks like a flower bud. When the petals of all bud-looking units unfold they form a flat space covering-structure (Figure 11).

An additional advantage of the proposed approach is that by integrating to the digital kinematic model of the origami type structure, architecture parameters such as color, texture, surface translucency, light, shadows, etc, a more thorough study of the architectural features of a transformable origami type membrane structure can be achieved.

5 Summary and Conclusions

This paper is based on the assumption that principles of the origami art and math can find applications in the conception and design of transformable membrane structures for architecture. Characteristic features of origami-type structures include the following: a) they are subject to mathematical conditions that apply to origami paper constructions and b) they involve more than one geometric configurations which are the result of a complex kinematic process, and as such they are difficult to represent and visualize.

The paper the basic mathematical conditions that set the necessary geometric and topological framework within which existing origami patterns can be understood or new ones can be created, have been identified and described. For the study of origami-type structures, in addition to the tradition approach of paper model construction, a computer simulation and visualization method that takes into account the origami kinematics and integrates the mathematical conditions is proposed.

The proposed method has been used for the morphological exploration of architectural structures based on origami concepts. Two different applications of architectural membrane folding have been studied. This two-case study has shown how origami math is integrated in the computer visualization and kinematic simulation of these structures, and how animated simulations of the transformation process during folding can identify problems in their initial geometric conception. The method has helped us to further explore the applicability of existing origami concepts and to invent new methods of membrane folding. The study has also shown that the proposed method allows for an exploration of the effect of geometric parameter variations on space definition and enclosure, as well the effect of inherently architectural parameters such as color, texture, surface translucency, light, and shadows on the morphology of a transformable origami-type membrane.

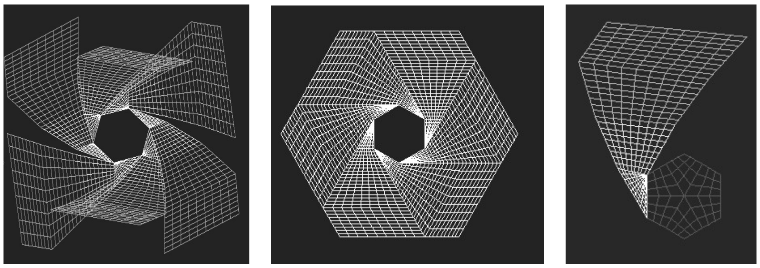


Figure 10

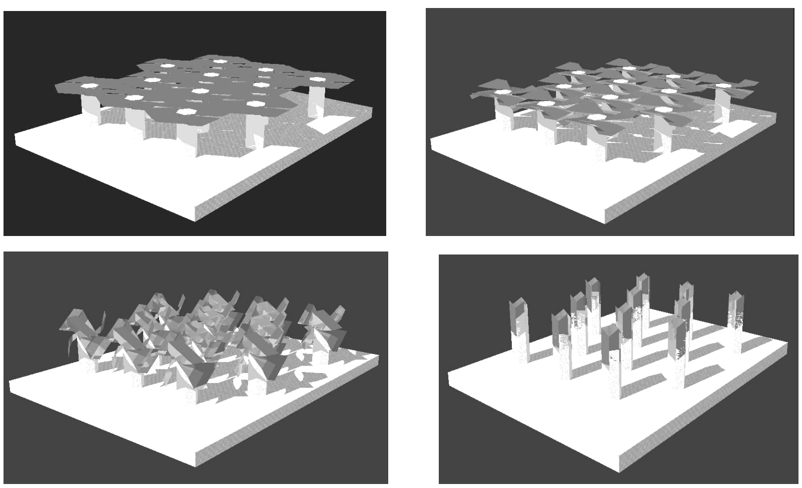


Figure 11

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