Digital Origami: Modeling planar folding structures

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This paper presents a surface manipulation tool that can transform any arrangement of folding planar surfaces without the need to custom program for each instance. Origami offers a finite set of paper-folding techniques that can be cataloged and tested with parametric modeling software. For this work, Rhinoceros and Grasshopper have been chosen as a software platform to generate a parametric folding tool focusing on single surface folding, particularly where surfaces can transform from one configuration to another while retaining their planarity.

Folding surfaces, particularly complex crease configurations can be modeled digitally and tested in variation using this algorithm. This makes it possible to design and test any folding pattern configuration by simply creating a flat tessellation pattern. Because this algorithm is inherently without scale, it has the potential to be implemented on a wide range of applications including retractable walls, roof structures, temporary structures, tents, furniture, and robotics.

1 Introduction

To fold something is to lay one part back onto itself. In this sense folding is neither subtractive nor additive, but instead is self-referential. The most intriguing moment of the fold is the cross from one dimension into another. If you crumple a piece of paper it will take the properties of a three-dimensional shape, though the paper is still a two dimensional surface. With a combination of simple folds one piece of paper may address some fundamental aspects of architecture by acting as both structure and skin simultaneously (figure 1).

As an analog parametric technique, paper folding has its limitations. Working with folding planar surfaces in digital modeling applications is equally problematic because one is normally only able to reposition components locally, one at a time. When modeling transformable surfaces it is helpful to be able to visualize surface movement, but there is currently no way to globally affect rigorous surface transformations without custom programming for each individual case. This research proposes a parametric surface manipulation tool using that can transform any arrangement of folding planar surfaces without the need to custom program for each instance.

2 Paper-folding Procedures

Origami, the Japanese art of folding paper into intricate designs and objects, provides precedence for mathematics, science, art, and architecture. Certain geometrical problems, such as trisecting an angle and doubling a cube are impossible to solve with a compass and straight edge, yet possible with paper folding. Origami works through its own geometrical rules based on the relationship of lines, points, and planes. The mathematician Humiaki Huzita formulated six axioms that map points and lines to help construct and explain folding schemes. These axioms are based on the fact that folding is an accurate and precise quantifiable operation. The sequence and shape, or the relationship between surface and points of an origami object, can be defined by rules and these can be viewed as a type of manual algorithm (Demaine, 2007).

Paper-folding is inherently an algorithmic process involving sequences of creases and folds that are designated with a positive, mountain, direction or a negative, valley, direction. Origami corrugation is a technique of alternating mountain and valley folds in an arrangement that allows movement in a folded model. These patterns have certain properties. A corrugated model that can fold flat will have an even number of vectors entering one vertex (figure 2). A corrugated model that can fold up in one direction contains one pleat or one set of alternating mountain valley folds (figure 3). A model that can fold in two directions possesses a primary and secondary pleating.

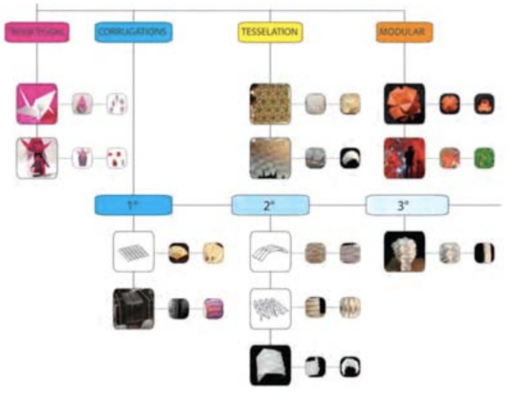

Figure 1. Origami Classifications and architectural speculation.

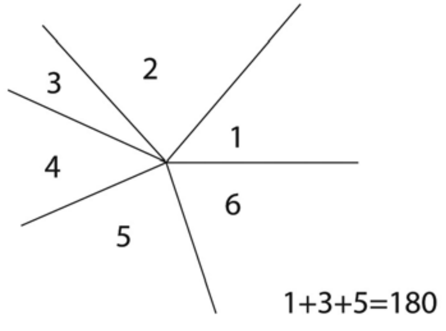

Figure 2. Flat foldability. The number of creases meeting at a vertex must be even and the sum of every other angle must equal 180 degrees.

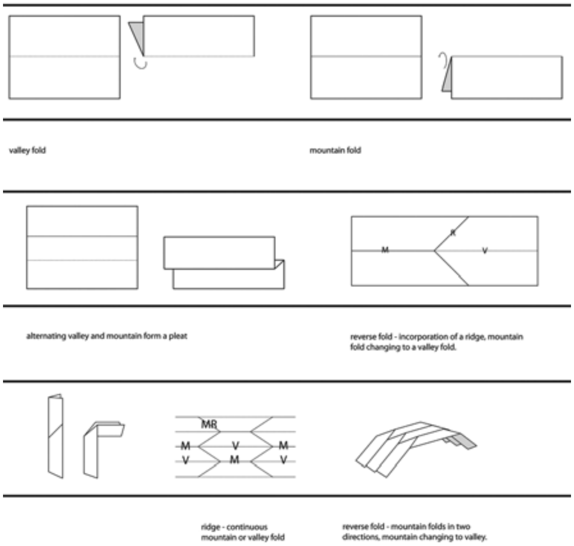

Figure 3. Mountain and Valley folds.

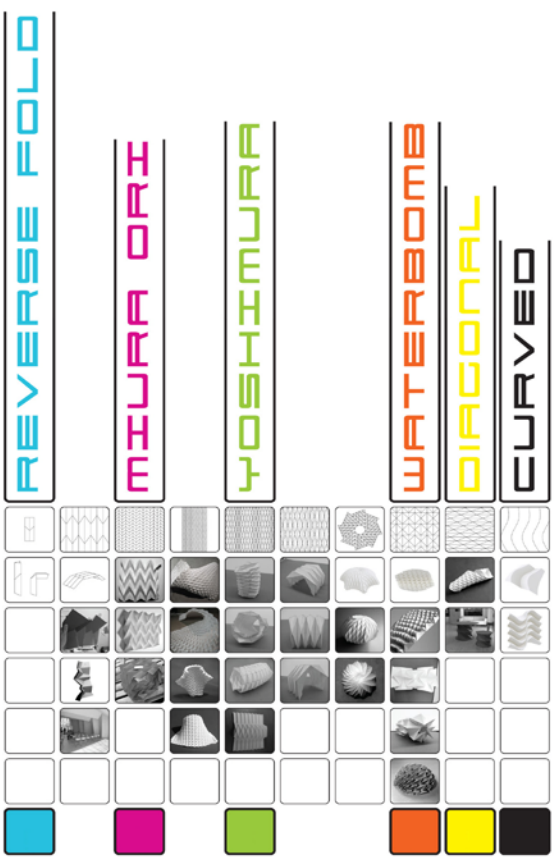

Figure 4. Variations of folding types.

There are five essential folding techniques including the reverse fold, miura ori, yoshimura, waterbomb, and diagonal (figure 4). Each possesses unique formal qualities and a unique range of motion. (Figure x represents a matrix of folding techniques and possible applications.

The flexibility of the folding technique allows for an almost infinite number of variations to be created by manipulating the crease pattern (Demaine, 2007).

3 Digital Origami

The tool that was developed uses the surface crease pattern to define the possible movement of the digital model. If the surface's form is manipulated, the base crease pattern will automatically adjust to the deformation, yielding a new pattern with the same surface topology. Several folding (kinetic) analog models were created leading to the development of the algorithm, each using variations of origami folds.

In constructing a catalog of folds, constraints and an embedded range of solutions the Grasshopper graphical algorithm editor was used in concert with Rhinoceros. The algorithm works by defining a sequence of operations linked to the various folding properties of the five folding types investigated. There is a root folding sequence that may be repeated as many times as desired, essentially a kinetic pattern (figure 5). Each subsequent surface is defined off the original geometry through a series of commands: move, mirror, and rotate. The simulation of the digital folding of the model is decidedly more complex to define since the kinetic movement of repeated folds must have their own axis and center of gravity as well as be linked to those of the entire surface.

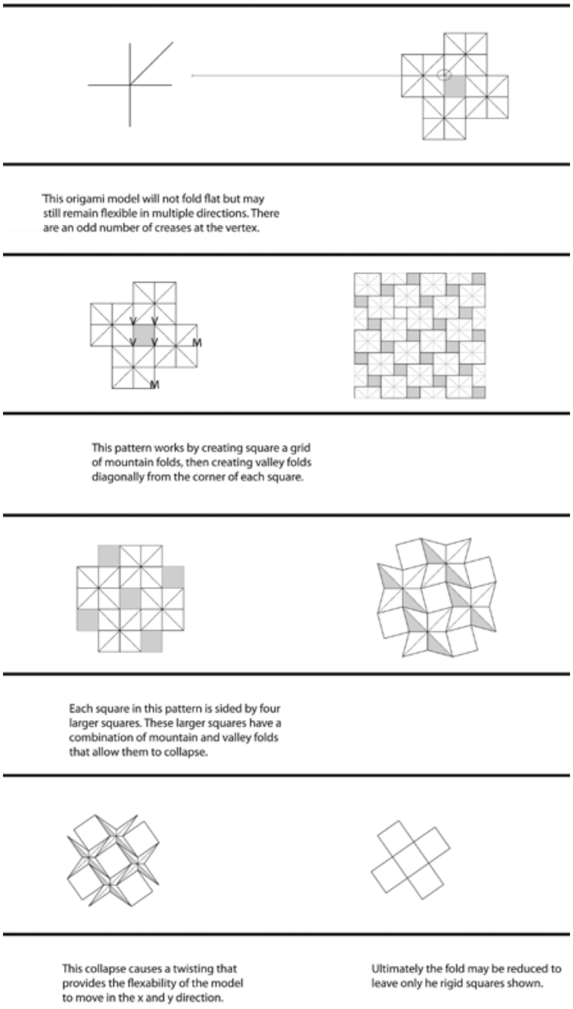

Figure 5. Waterbomb folding morphology.

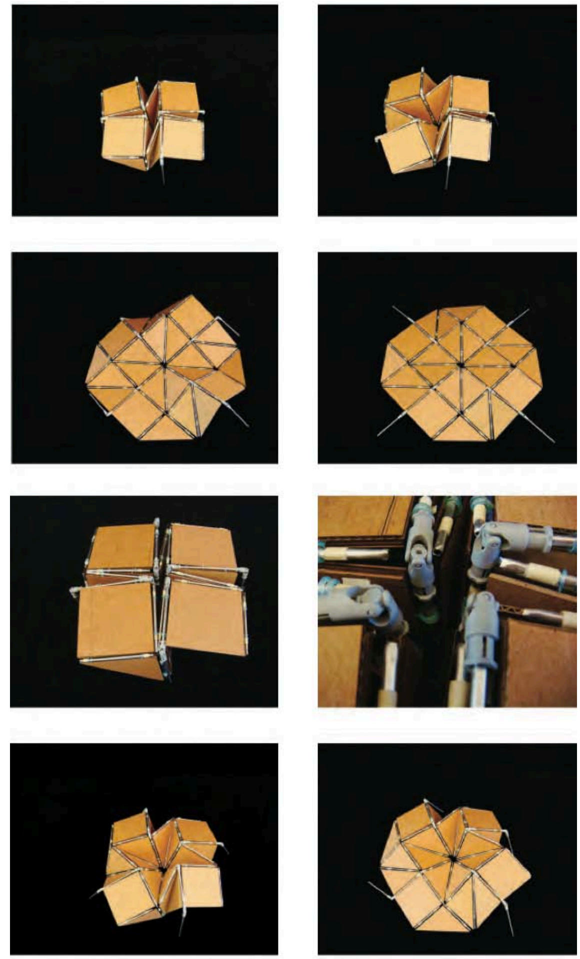

Figure 6. Using a universal joint as a torque converter to allow mechanical movement of the system.

4 Scalability: Joints + Connections

The digital simulation provides precise data on the size of the model when it's expanded and when it's collapsed. This is the first step in being able to use this model on a large scale. One consideration that must be accounted for when scaling this work for architectural production is the thickness of material. Tomohiro Tachi (Tachi,2010) has presented research that explores this problem with consideration of the fold, to account for the theoretical complete collapse of two faces upon one another.

4.1 Return to Analog

Another important factor, and one explored in greater detail with this project, is the potential for the kinetic movement of a paper-folding sequence to be actuated at human scale. While some of the folding types move along only one axis, the Waterbomb fold moves simultaneously in four axes. A mechanical folding of the Waterbomb was explored that acts along the surface of the material so as not to interrupt the topology of the sheet.

An analysis of the movement of each face in the system led to an discovery that it is possible maintain the kinetic movement of the system by rotating along a single edge of each face. This allowed us to trace uninterrupted paths of movement from end to end, through the surface of the system. Mechanically, this was executed by connecting certain axes with a universal joint (figure 6). This joint allows torque to transfer from one structural member to another through torque conversion. The torque then provides the energy to fold the model. Origami possesses similar traits to textiles and fabrics. The pleats allow for creating structure with a thin material.

5 Limitations

One challenge that emerged during the testing of this program was that of intersecting surfaces. To correct for surface intersections, it was necessary to check endpoint coordinates and connectivity of each face such that that they did not intersect.

In order to rigorously preserve the geometry of the system it was necessary to be certain that each face was completely flat at every stage of the folding process. To ensure this, a planarity test was embedded into the program. Currently, the algorithm allows for quadrangles and, to account for elasticity, triangulation of the tessellated surface. However, the algorithm does not yet have the ability to predetermine strict planarity of quads when using custom folding patterns.

6 Conclusion

Because origami is bound by physical the physical limitations of paper size, paper thickness, and number of folds it is useful to explore variations using digital tools that may otherwise be unrealized. Folding surfaces, particularly complex crease configurations, can be modeled digitally and tested in variation using these algorithms. This makes it possible to design and test any folding pattern configuration by simply creating a flat tessellation pattern.

References

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