Single Degree-of-Freedom Rigidly Foldable Origami Flashers Based on Curved-Fold Model

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Introduction

The purpose of my proposed research is to explore the application of curved folding in the design of wrapping surfaces. In recent years, origami has found applications in efficiently packing surfaces that easily deploy, but the design of optimal fold patterns remains an open field of investigation. The particular fold patterns that we investigate are known as “flashers”– patterns that can be packed tightly and deployed dynamically in one continuous motion. We propose to investigate the applications of one novel flasher pattern in packing both rigid and flexible, finite-thickness materials.

Various flasher patterns have been proposed during recent years as demand has increased for devices such as foldable solar arrays, but these models are based on idealized zero-thickness models that are normally incompatible with mechanical designs for the following reasons:

1. <u>Thickness Accommodation</u>- As shown by Tachi [1], adding thickness to such models often fails to allow proper actuation of joints and creases. Tachi suggests that some of these thickness problems can be avoided by trimming panels near joints, but most flasher models do not allow for the added spacing that this requires.
2. <u>Self-Intersection</u>- As shown in Lang et al. [2], models that are compatible with finite-thickness designs may not allow proper deployment due to the collision of sections during the transformation.
3. <u>Over-Constrained Motion</u>- As demonstrated by Tachi [3], most fold patterns using quadrilateral sections and degree 4 vertices are over-constrained, but by using a single repeated vertex, it is possible to achieve a single degree-of-freedom.

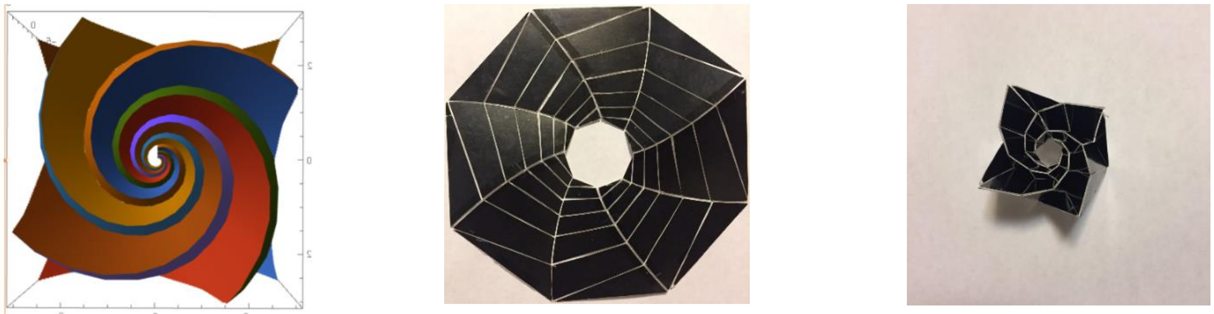
Previous work at BYU by Zirbel et al. [4] proposed solutions to a few of the problems created by finite-thickness models and recently developed one thickness-accommodating model as shown in Lang et al. [2] that allows rigid deployment but uses a single cut along crease lines to avoid self-intersection. Such a cut is non-ideal as it complicates the deployment process and requires a more elaborate deployment mechanism.

Preliminary Work

In recent months I have done preliminary work on an alternative flasher pattern, based on a curved-fold model, that shows great promise in addressing issues of finite-thickness, self-intersection, and over-constrained motion. While working with Dr. Corey to model and explain the logarithmic nature of spiral tie-dye t-shirts we discovered that by folding along logarithmic curves we could create a curved fold flasher model that reaches a bound state before it completely wraps (this bound state is shown in figure 1a). One useful property of the curved-fold flasher is that the position of the ruling lines (or lines with zero *Gaussian* curvature) is constant with respect to the surface. This result, along with a few properties of logarithmic curves allowed us to produce a discretized rigid-panel flasher model shown in figure 1b&c. Additional folds may be introduced to restrict the height of the folded state and increase volume efficiency, we do not plan to focus on these additional folds until the properties of the fundamental flasher pattern are well defined. This discretized model fulfills each of the fundamental conditions for flat foldability of degree-4 vertices set forth by Evans et al. [5] and we hypothesize that this model addresses each of the aforementioned issues in the following ways:

1. <u>Thickness Accommodation</u>- Because the model reaches its bound state before sections meet, the model is naturally spaced to accommodate thickness as proposed by Tachi [1].
2. <u>Self-Intersection</u>- Due to properties of the logarithmic curves that sections follow, the model avoids self-intersection in all intermediate states.
3. <u>Over-Constrained Motion</u>- Because the model uses a single repeated degree-4 vertex, a single degree-of-freedom is obtained.

A key element of my proposed research will be to mathematically prove these properties along with the overall rigid foldability of the discretized model. We also propose to perform a more advanced analysis on the curved-fold model and determine its effectiveness in wrapping finite-thickness flexible materials.



(a) (b) (c)

Figure 2: (a) Computer generated curved-fold model in bound state.
(b) Discretized surface; unfolded. (c) Discretized surface; folded.

Challenges

While the proposed flasher model is potentially the first to allow rigid, finite-thickness panel deployment without the use of a cut it also presents a few unique challenges. The most notable is that the central polygon is not fixed, and shrinks at a rate proportional to the boundary when the surface is wrapped. This behavior is non-ideal in applications such as space travel where an array should wrap around a fixed hub. This issue may be addressed through use of an actuation mechanism at the center. The rate at which this mechanism regulates the contraction of the central polygon is important to limit stress in panels. We plan to address the issue of such a mechanism after the properties of the flasher model are well defined.

Approach

To prove the rigid-foldability of the flasher our work will rely on a heavily analytic approach, using an method similar to that defined in [5]. Once this work is complete we plan to define relations between panel thickness, and folded flasher height to determine the curves that will be used to create the original fold pattern. In my preliminary work I have established a loose theoretical upper limit on this relationship but we plan to tighten this limit through the use of computer generated and physical models. Models will be produced using rigid panels on a flexible backing to simulate joints.

Conclusion

The anticipated academic outcome of the proposed research is to understand the properties of our novel thickness accommodating flasher model. We plan to publish these results in a peer-reviewed publication. My firm understanding of the mathematics of the curved fold surface and creativity in initially discovering the surface qualify me to perform this research. My mentors' knowledge of the field and familiarity with the publication process will allow us to produce innovative and timely results on the applications of origami in mechanical design.

Sources

[1] Tachi, T., 2011, "Rigid Foldable Thick Origami," Origami 5, Fifth International Meeting of Origami Science, Mathematics, and Education, p. 253-264.

[2] Lang, R. J., Magleby S., Howell L., 2016, "Single Degree-of-Freedom Rigidly Foldable Cut Origami Flashers," ASME. J. Mechanisms Robotics. 8(3), p. 031005.

[3] Tachi, T., 2009, "Generalization of Rigid Foldable Quadrilateral Mesh Origami," 50th Symposium of the International Association for Shell and Spatial Structures, Valencia, Spain, Sept. 28–Oct. 2.

[4] Zirbel, S. A., Lang, R. J., Thomson, M. W., Sigel, D. A., Walkemeyer, P. E., Trease, B. P., Magleby, S. P., and Howell, L. L., 2013, "Accommodating Thickness in Origami-Based Deployable Arrays," ASME J. Mech. Des., 135(11), p. 111005.

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