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A Novel Deployable Telescope Baffle Using the Kresling Origami Fold

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ABSTRACT

This report introduces a novel deployable origami baffle designed for telescopes and optical systems, which reduces stray light while maintaining high compactness ratios and low weight. This design leverages the planar nature of the end caps on a cylindrical Kresling origami fold to incorporate mounting points, deployable options, and baffle vanes. The adaptable nature of origami (number of faces, origami geometrical ratios, scaling, etc.) allows the design to easily conform to system requirements, including field of view, deployed length, stowed/deployed stability points, and available volume.

Geometric ratios that exhibit bistability in both the stowed and deployed states are discussed in detail, as this results in a rigid structure that maintains its desired configuration. Several designs were conceptualized, and multiple small-scale prototypes were constructed. Potential applications include camera lens hoods, lightweight astronomy telescopes, and deployable baffles for space telescopes and optical systems.

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1. INTRODUCTION

Despite its ancient origins, origami is currently being revisited in novel implementations to solve tough engineering challenges. Several modern examples are: deployable solar arrays for spacecraft [1], pneumatic robotic actuators [2], medical devices [3], ballistic shielding [4], deployable antennas [5], and many others. At its core, origami can be viewed as a pattern of one degree-of-freedom hinges on a semi-flexible substrate. Several repeatable origami geometries have been discovered, such as the Yoshimiura [2], Miura-ori [6], Flasher [1], Kresling [7], and the recently discovered Origami Claw Tesselation [8]. These geometries are of special interest because they are flat-foldable with high compression ratios and are roughly one degree-of-freedom as an assembly. Some deploy cylindrically, some deploy linearly, and others deploy circularly, providing multiple options for engineering solution spaces.

The Kresling fold is one of the first engineered folds discovered; when a thin walled cylinder is torsionally buckled, it naturally creases into this shape [7]. Current research has expanded upon this concept by varying the number of tesselations on a side, the ratios between vertexes, and the angles between vertexes, leading to several key conculsions. This fold can be modified to have multiple stability points, which are locations where the strain in the folds are at a local minimia [7]. It can also be designed to maintain internal stresses while stowed, allowing it to deploy without the application of external force [9]. The geometry can be tailored to change its overall packing ratio, deployed height, footprint, and many other useful design parameters for constrained environments. Another observation of the Kresling fold is that the ends of the cylinder are ideally planar between its stowed and deployed states, allowing for stiff interfaces to be attached. Overall, this fold deploys from a flat-packed, disk-like stowed state into a much taller hollow cylinder.

One major application area for a flat-packed cylinder with multiple planar surfaces is as a lens hood or a baffle for optical systems. The basic concept behind this application is to reduce the amount of stray light reaching the optics, thereby improving image quality. Tradionally, these baffles are made of stiff materials and become quite large when paired with optical systems that have a small field of view. For terrestial cameras, this usually constitutes a stiff piece of plastic that occupies significant space in equipment bags. For spacecraft, however, this is a major design hurdle as mass, volumetric constraints, and mechanical limitations further complicate the design.

Spacecraft light baffles tend to be made of very stiff yet lightweight materials, as heavier designs impose penalities on both the spacecraft and the mechanical survavilibilty of the baffle interface during launch. Thus, materials such as carbon fibers and fiberglass are used as much as possible [10][11]. These baffles are typically located near the exterior of the spacecraft, ncessitating engineering trade-offs to avoid the keep-out zones of the rocket's fairings. To mitigate these trade-offs, several deployable baffles for spacecraft have been designed and published [11][12][13][14]. As these baffles are stowed during the assent on the rocket, the mechanical stresses are significantly lower, allowing volume to be allocated to other parts of the spacecraft. While these designs alleviate some mechanical constraints, the stowed ratios are often modest and can be mechanically complex. At the cost of a deployment mechanism, a deployable origami baffle can enable increased baffle lengths, highly efficient stowed ratios, and can be easily modified to fit the overall mechanical constraints.

2. GEOMETRIES

Several variables are used to define a Kresling fold, side lengths a/b/c, angles alpha/beta, and number of sides n. Figure 2-1 shows a single unit geometry that defines the Kresling fold, while Figure 2-2 illustrates this unit geometry in a Kresling fold where n=6 and mirrored across the top plane to maintain a constant overall assembly rotation. Not all of these variables are not required to fully define the geometry of the fold, which may be omitted in the following sections.

The overall fold design can be simplified to a pattern of parallelograms with folds down one of the diagonals. The edges of the parallelogram are all folded in a 'mountain' fold, while the diagonals are folded in a 'valley' fold. Once the folds are set, the entire assembly should wrap into a cylinder, with the vertex of one external parallogram meeting the external vertex of the parallogram in the same row.

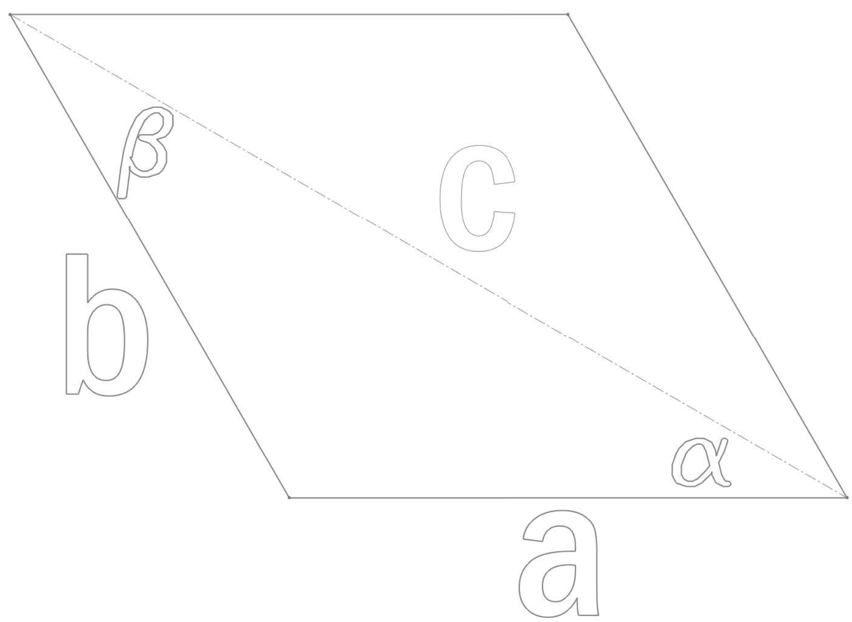

Figure 2-1. Kresling unit geometry, a=4", b=4", c=6.93", α=30deg, β=30deg

Using the fold patterns from Figures 2-1 and 2-2, the resulting folded assemblies are generated. Figures 2-3 and 2-4 depict the deployed form of the assembly, where the diagonal strain energy is zero. Isometric and side views are provided, as 3D representations of origami can be difficult to intrepret. Applying force to the assembly will transition it to its packed form, as shown in Figure 2-5, which is the point where all of the triangular faces are in contact with the next set of faces. While this is also a state where the diagonal strain energy is zero, any physical manefestation of this Kresling assembly would still experience some disturbance forces within the material, as

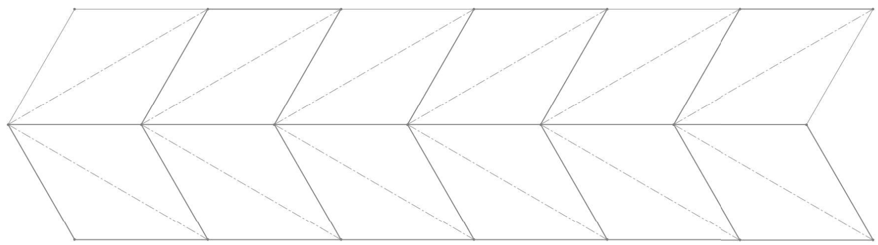

Figure 2-2. Kresling flat pattern, n=6, mirrored for overall assembly rotation to remain constant

thicknesses are non-zero. Material bent around an edge would naturally have some disturbance force due to the outer radius of the crease and the inner radius being unequal. However, the significance of this effect in practice depends on the geometric pattern, which drastically changes the amount of force required to move the assembly along its axis.

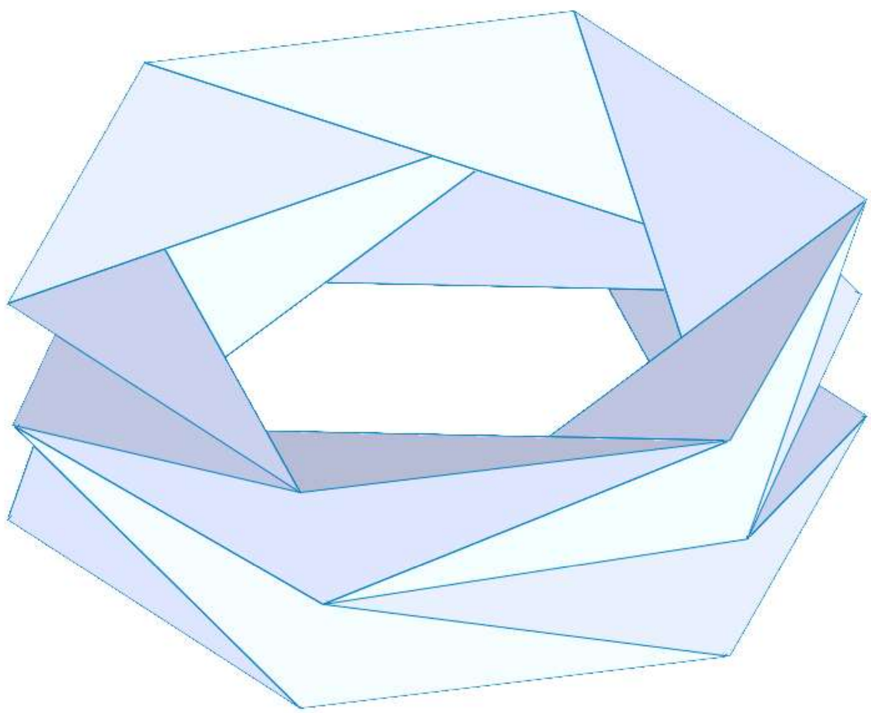

Figure 2-3. Deployed Kresling pattern, n=6, folded into a 3d assembly

It is important to note that between Figures 2-3 and 2-5, the geometrical interface of the bottom of the cells remains constant in a hexagon configuration. This is a hexagon since the pattern uses n=6 sides. Increasing the number of sides would create a constant n-gon configuration between the folded and deployed states. Any rigid plate that mounts to these surfaces will maintain the same n-gon interfaces throughout the folded and deployed states. This property is useful for a number of applications, which will be discussed in the following sections.

Modifying the goemetric parameters of the unit cell and number of cells dramatically changes the overall response of the assembly. For more details on equations governing vertex strain energies,

Figure 2-4. Deployed Kresling pattern, n=6, folded into a 3d assembly, side view

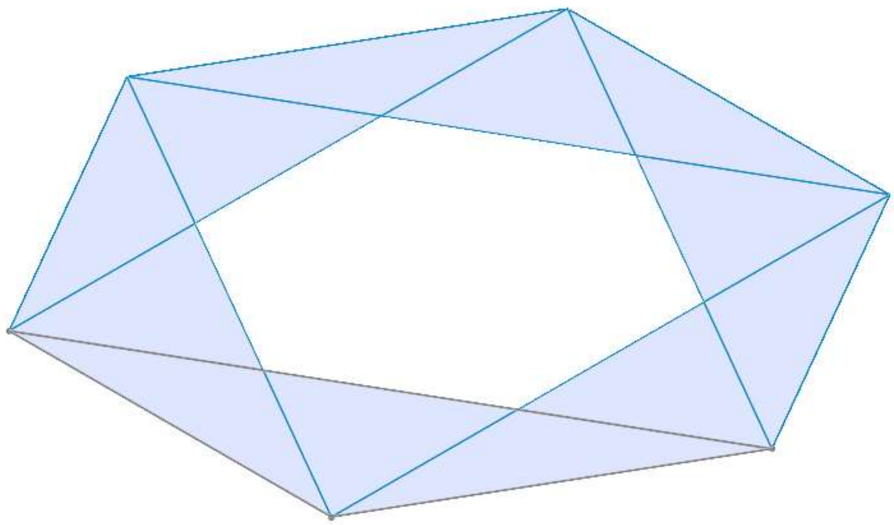

Figure 2-5. Packed Kresling pattern, n=6, folded into a 3d assembly

assembly fold angles, and other relevant parameters, see reference [7]. Several other papers identify stability points and other useful assembly properties in the Kresling fold; see references [5][6][9][13][15][16].

As these structures maintain constant interfaces, the overall number of layers can be infinite. This allows for a cylindrical assembly whose height is easily modifyable by adding more layers. The geometry patterned in Figure 2-3 creates an assembly whose layers alternate rotation directions, resulting in a structure that maintains its rotation throughout deployment. Figures 2-6 and 2-7 show two views of a stack of alternating Kresling geometries with 16 layers which will deploy linearly. Figures 2-8 and 2-9 show two views of a stack of 16 layers whose Kresling geometries are all oriented in the same direction, resulting in an assembly that rotates helically as it deploys. Both configurations can be useful for different applications which will be discussed further below.

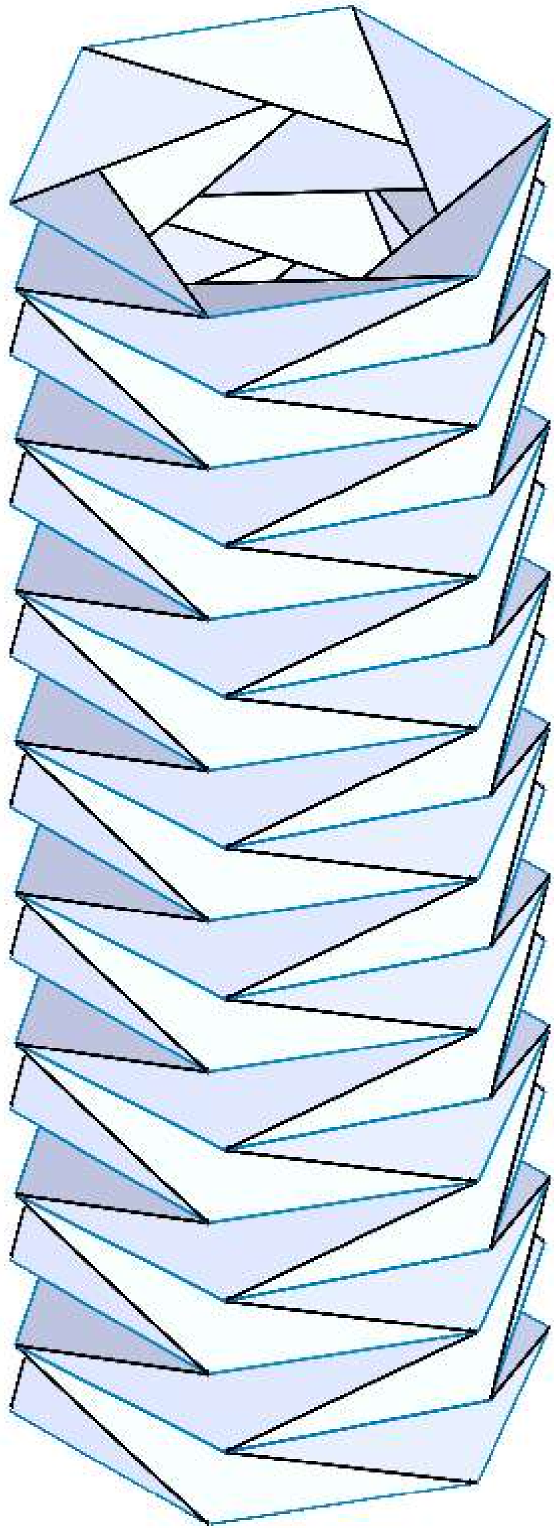

Figure 2-6. Isometric view of a Kresling assembly with 16 alternating layers

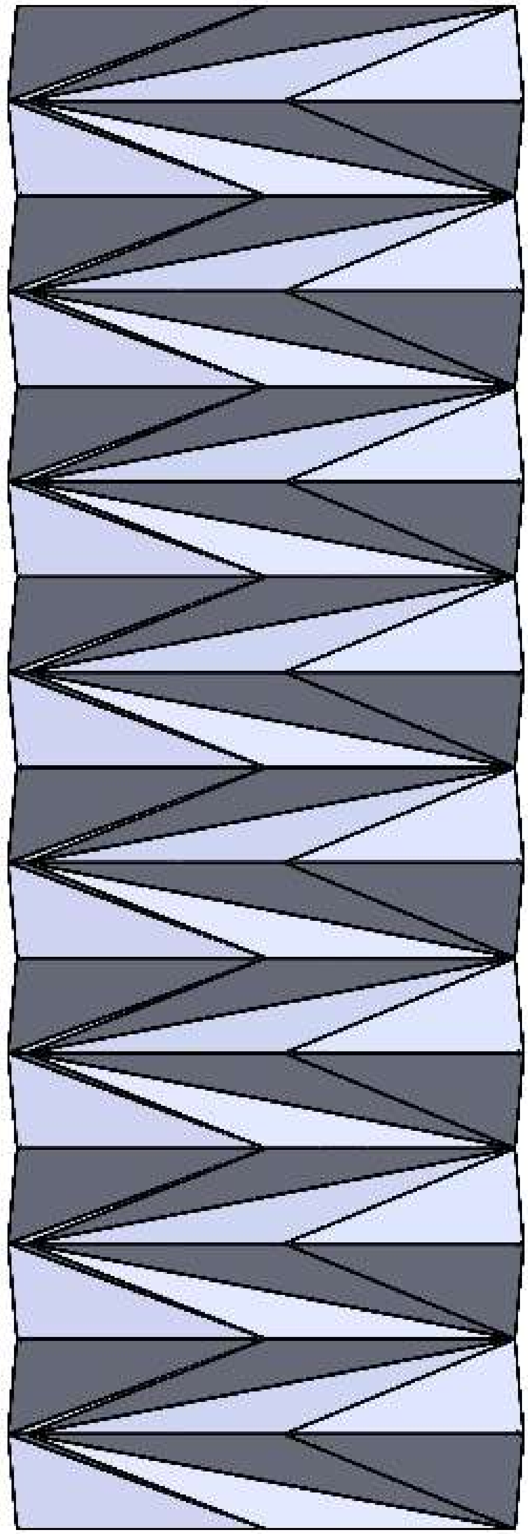

Figure 2-7. Side view of a Kresling assembly with 16 alternating layers

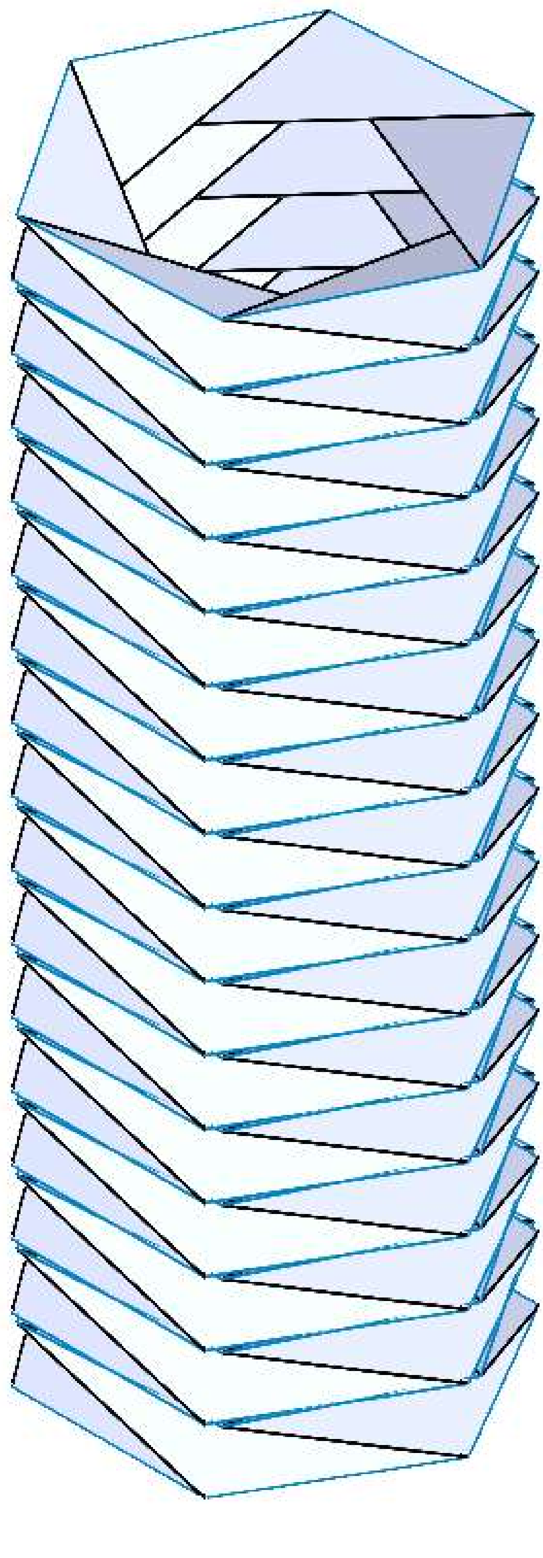

Figure 2-8. Isometric view of a Kresling assembly with 16 identical layers

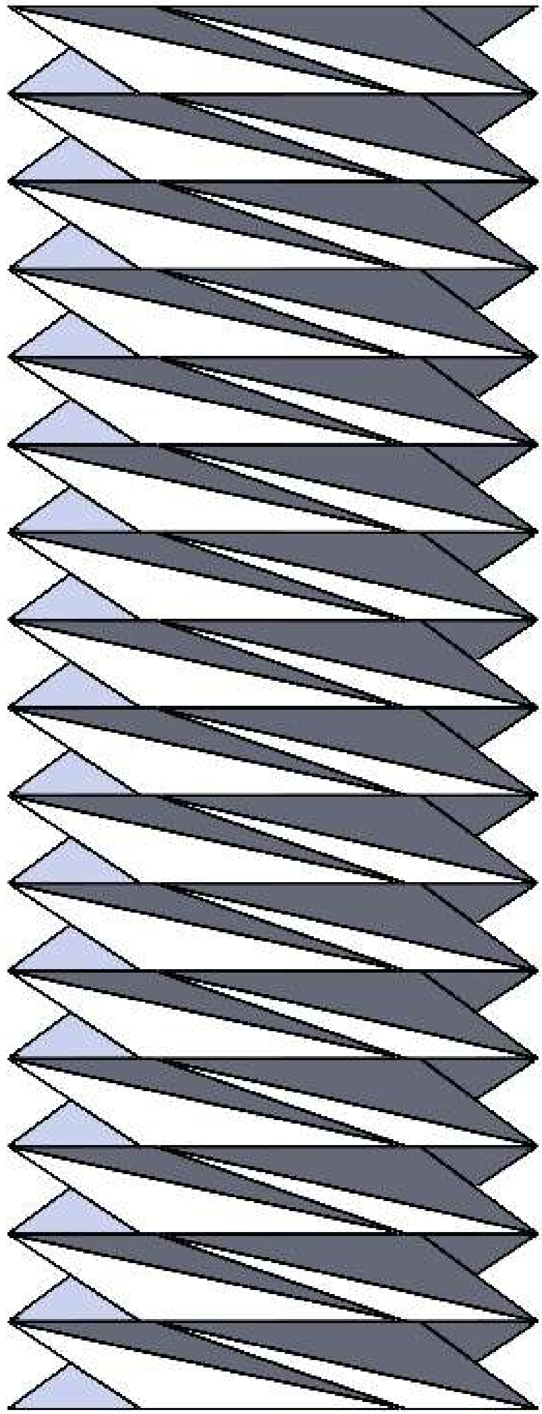

Figure 2-9. Side view of a Kresling assembly with 16 identical layers

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3. PROTOTYPE

With the basic premise of planar flatness of the end caps identified, a prototype was designed, manufacturered, and tested to confirm the effacacy of the design. The most promising design for a deployable baffle would use a bistable geometrical design, stable in a fully flat configuration and fully deployed configuration. Multiple layers would be used to attach several vanes along the length of the baffle with holes of specific sizes in them to align with designed optical field of views. A fully stable design was also prototyped with mixed results for experimentation which is detailed below.

The bistable prototype used the geometries identified in [7] to create a bistable structure that was stable in the fully flat and fully depoyed configurations. Using an arbitrary n=6, the a/b/c ratios vertices of the unit cell were 1/1.5/1.9605. A single row of this geometry is seen below in Figure 3-1. A side length of 2" for the side closest to the sensor was used to make it easily manufacturable but not unweildy. Sections closer to the aperture opening were designed to be larger as the vanes grow in diameter to account for the field of view. Moving away from the sensor side of the baffle, side lengths of 2"/2.25"/2.5"/2.75" were used with the same unit cell ratios to maintain similar strain energies. Since the assembly end caps are all planar, these non-identical geometries can still mount to these caps for manufacturing purposes. One interesting detail of this design is that the axial twist of each section is the same as they are defined by the ratios of the verticies, not the overall magnitude of the vertex.

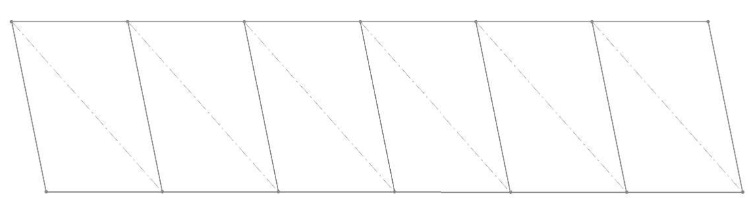

Figure 3-1. A Kresling bistable geometry with a=2", b=3", c=3.921", n=6

With the overall design dimensions identified, a CAD model of the stowed/deployed state was generated in SolidWorks with baffle vanes at every end cap. Cuts were made in the end caps where the vertices met up for tabs to slot into them for assembly purposes. See Figures 3-2, 3-3, 3-4, and 3-5 for multiple views of this assembly. This assembly had all of the layers oriented in the same direction, thus the entire assembly will significantly rotate as it transitions from its stowed to deployed states.

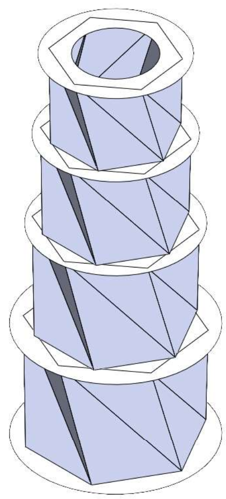

Figure 3-2. A four layered Kresling Bistable Baffle assembly, iso view

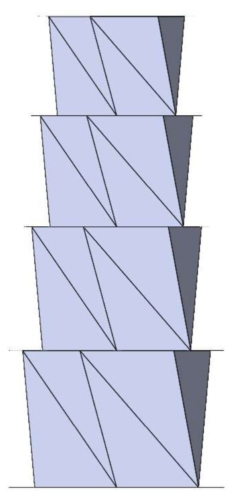

Figure 3-3. A four layered Kresling Bistable Baffle assembly, side view

Holes were cut in the origami planar end caps of varying size to meet the requirements for a 7deg optical field of view, resulting in an overall assembly that has a 28deg light exclusion angle and a total deployed length of 13.8". The field of view of the baffle are shown in Figure 3-6 and the light

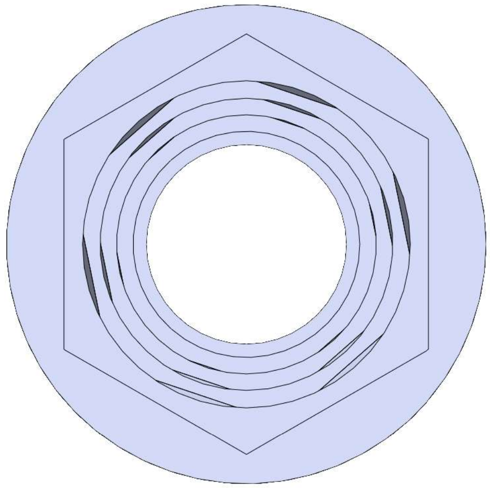

Figure 3-4. A four layered Kresling Bistable Baffle assembly, axial view

path traces are below in Figure 3-7. The benefit of a deployable origami system such as this is that if requirements are such that the light exclusion angle needs to be tighter, more stacks can easily be added to the baffle.

A number of prototypes using the above design and other bistable designs were created using a Cricut cutting machine on 67lb paper, cutting tabs in the interface vertices to insert into slots in the end cap interfaces. These were then adhered in place to prevent unwanted movement. One example prototype used the same 2"/2.25"/2.5"/2.75" vertex lengths with a/b/c/ ratios of 1/1/1.732 in a stable configuration defined in the Geometries section. Figure 3-8 shows both prototypes in their stowed configurations, the baffle on the left is the stable design, the one on the right is the bistable design. As it can be seen, they are slightly raised as the strain energies in the verticies from folding the paper are applying a slight amount of force to the assembly. The areal gaps are noticably different between the two designs, as the "c" vertex of the bistable design is longer, the triangular faces obscure more of the stowed area of the optical path.

In Figure 3-9, the deployed configuration of the stable design is seen. This configuration required a constant force to remain in the deployed state, springing back to the stowed state after the force was released. Due to its lack of prominent stability points, it is relatively easy to transition between deployment states. However this is difficult to properly utilize as an optical baffle as the vanes are dependent on the amount of force used to displace the overall assembly.

In Figure 3-10, the deployed state of the bistable design is shown. The overall deployed length is 13.6", slightly off from the expected 13.8". This is likely due to tolerances in the manufacturing process, higher accuracy results can be obtained with a few identified design changes. Significantly more force is required to transition the baffle from its stowed to its deployed state, deforming the verticies in the intermediary steps. Over multiple deployment cycles, the paper started to warp and crease, indicating unsuitability of the material for baffles with high-accuracy requirements.

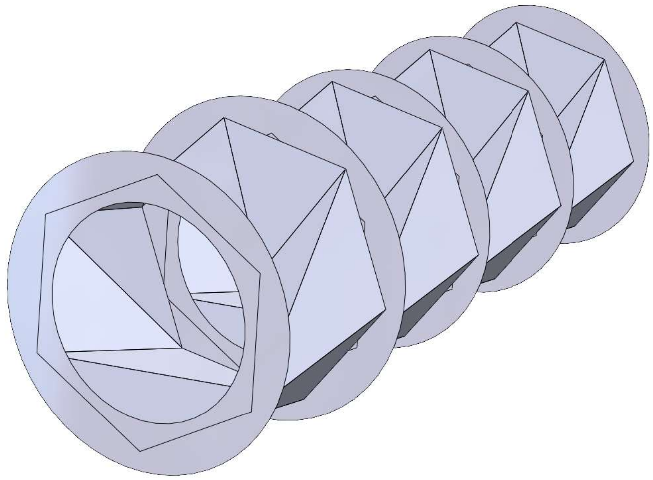

Figure 3-5. A four layered Kresling Bistable Baffle assembly, angled view

In its deployed state, the force required to transition it out of its deployed stability point is significant, providing a lightweight and rigid solution. Despite weighing only a ounce, it requires almost a pound of force to collapse it. Use of higher stiffness materials will further increase this stability force to maintain the locations of the vanes. Figure 3-11 shows an axial view of the deployed baffle with the vane rings clearly shown.

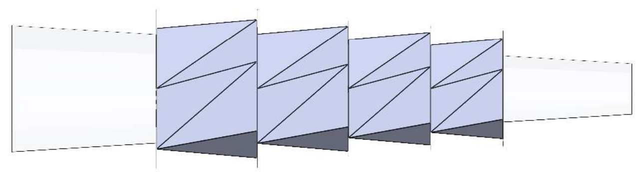

Figure 3-6. The overall field of view of the baffle, which is 7deg

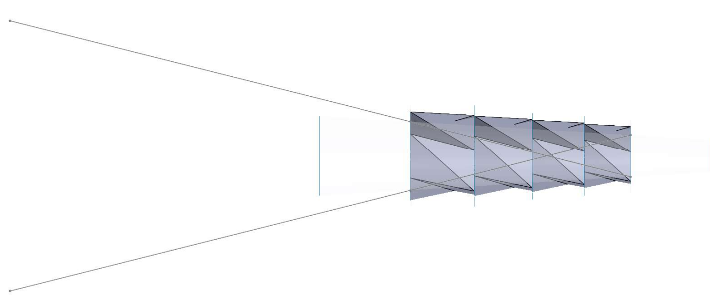

Figure 3-7. The overall light exclusion angle, which is 28deg

Figure 3-8. Stowed configuration of two baffle designs, stable 1/1/1.732 ratio on the left, bistable 1/1.5/1.9605 on the right

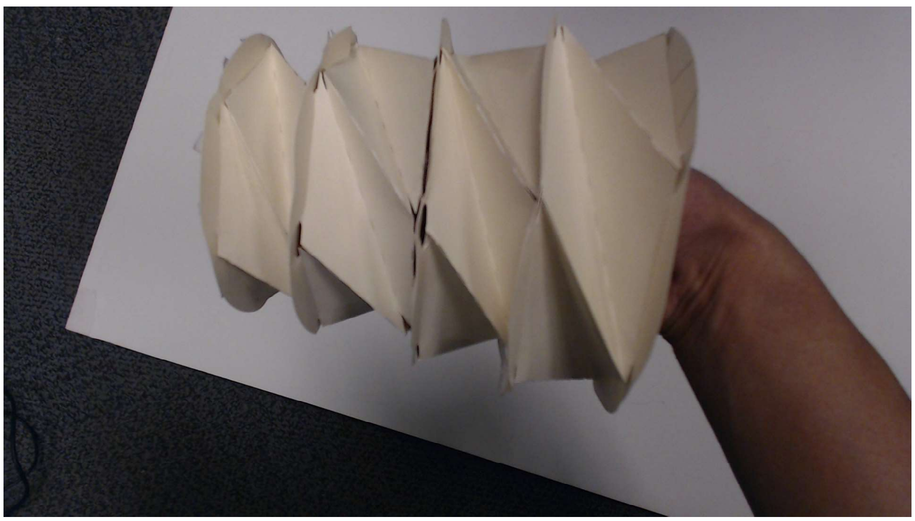

Figure 3-9. Deployed configuration of the stable baffle assembly

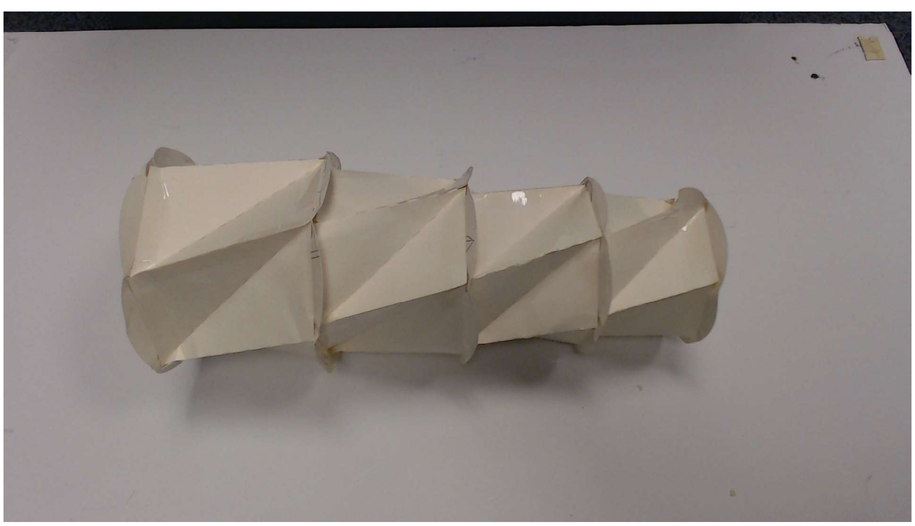

Figure 3-10. Deployed configuration of the bistable baffle assembly, side view

Figure 3-11. Deployed configuration of the bistable baffle assembly, axial view

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4. DISCUSSION

4.1. Deployable Methods

The tradeoff to implement deployable baffles for spacecraft is that for the compactness of the baffle, a reliable deployment mechanism is required to actuate it. Several options exist for this, the most reliable would be to couple the design with a rigid deployment mechanism such as telescoping rigid rods. If the satellite is long enough, these rods can be integrated with few difficulties. Another design that is rigid but compact is to use a deployable composite boom to provide deployment force as well as increasing rigidity of the overall system. There is a potential for directly integrating a spring into the surface of the origami to provide the axial deployment force but this will need further study.

Other options are to use inflatable sources, see reference [15] for several options. As the Kresling design can be made air-tight, sheathing the baffle with an inflatable tube or equivalent can provide the deployment energy for the system. However, this may cause issues with reliability and cleanliness with an optical system.

Finally, one option with the geometry of the baffle itself is to use rotational mechanisms to apply a helical deployment force by restraining the furthest end of the system and rotating the entire assembly. As the geometry would all be aligned the same direction, the axial displacement would likely cause the baffle to linearly displace. More investigation into this would be necessary.

4.2. Next Steps

Several avenues of research are required to implement this idea for optical systems, doubly so for deployable baffles on spacecraft. Baffle coatings would be required to absorb the scattered light hitting the sides of the Kresling structure. This coating would also need to be mechanically reliable as surfaces will be in contact with the coating, thus fragile coatings will be unusable. Simulations of optical scattering will be necessary to ensure that the tolerances in the construction and scattered light don't negatively impact the reliability of the baffle. Mechanical vibration simulations would also be necessary to ensure the structures stiffness.

More prototypes would be necessary to determine optimal material and geometric choices. It is likely that a hybrid of stiff but thin carbon fiber plates for the triangular faces of the Kresling fold and the vanes with a space-grade polyamide carrier material for the hinges would be ideal for this application.

4.3. Other Applications

The most straightforward application for this concept is for terresterial cameras, allowing photographers and astronomers to carry a easily stowed baffle for their DSLR/camera/telescope. As these would be deployed by hand, its designed requirements are greatly eased. This would need to be paired with optical systems with the same maximum field of view.

Using the Kresling pattern as a deployment mechanism, an array of bistable Kreslings that are oriented in the same manner can deploy several flat plates of varying materials to be used as a Whipple Shield, a design used on the ISS to protect the space station from small space debris. As the Kresling would not have major structural requirements once on orbit, almost all of the mass of the assembly would be dedicated to the Whipple Shield and not to the deployment mechanism. This would likely improve the areal mass of existing Whipple Shields and allow for larger spacings between layers, which increases the survivability of the shielding further.

One exciting application for a deployable baffle would be for deployable flat satellites (Starlink is an example of one such system), allowing several to be packed in a constrained volume and released once in space to enable large constellations of optical satellites. Hubble Space Telescope (HST) is used as an example below for this concept, as a large percentage of the overall length is the baffle, the structure was truncated at the secondary fold mirror suppports and replaced with a origami baffle. See Figures 4-1 and 4-2 for the baseline models of the HST and Space Shuttles from NASA's webpage [17] [18].

Using a notional n=72 sided Kresling design and a estimated packing ratio from the prototype, the overall length of the HST was reduced by around 13 feet. Figures 4-3, 4-4, and 4-5 are all of this change from deployed state of the origami baffle to its stowed volume. This however does not include the deployment mechanism but several concepts can be integrated to the outside of the spacecraft with few impacts. Finally, this model is shown in the bay of the Space Shuttle in Figure 4-6.

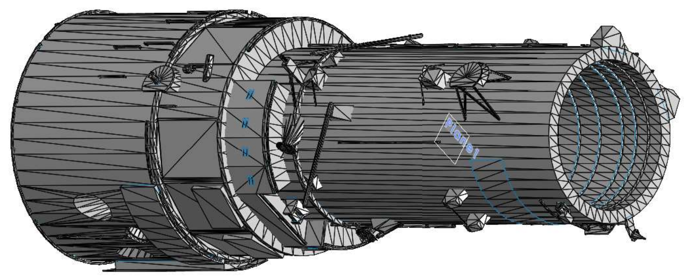

Figure 4-1. Normal model of HST with solar panels and aperature door suppressed

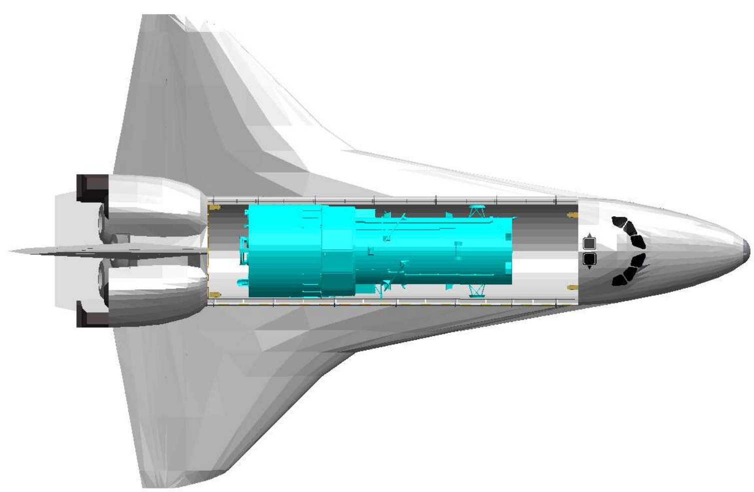

Figure 4-2. Example model of HST in the bay of the Space Shuttle

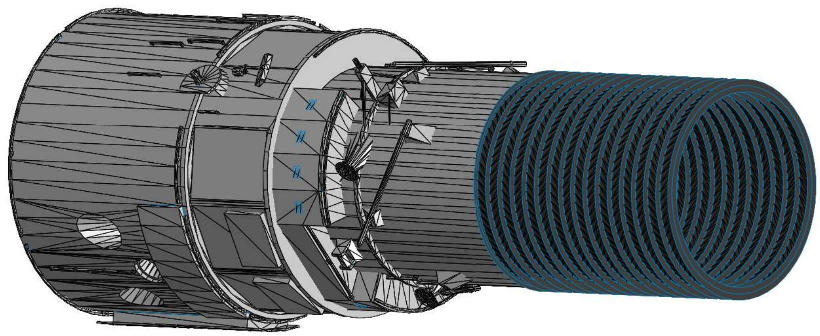

Figure 4-3. Example model of HST with the baffle tube replaced with origami baffles

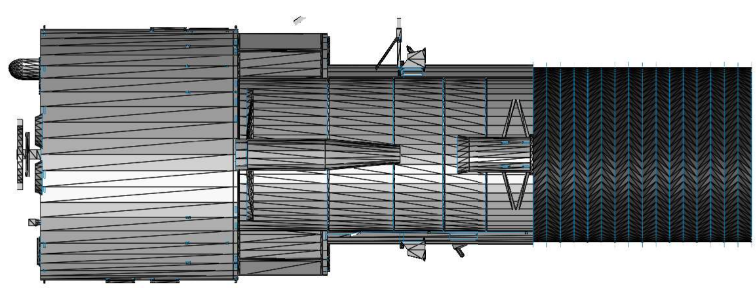

Figure 4-4. Example model of HST with the baffle tube replaced with origami baffles, cross section

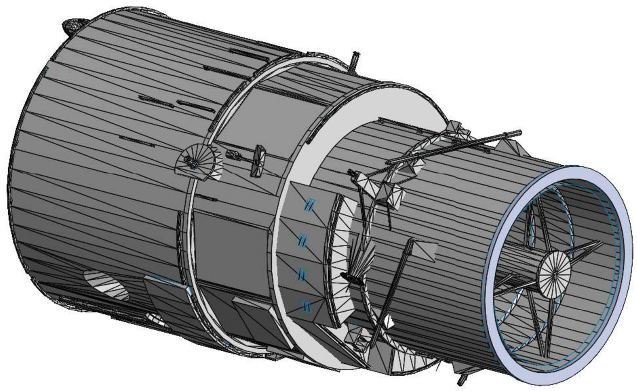

Figure 4-5. Example model of HST with the origami baffles stowed

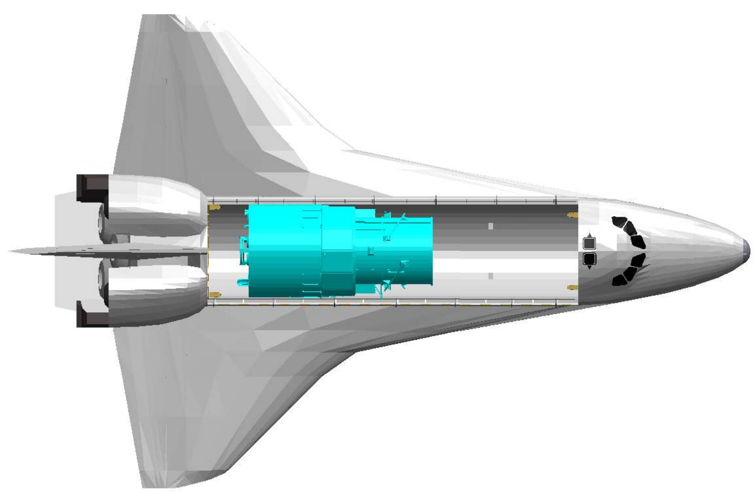

Figure 4-6. Example model of HST with stowed origami baffles in the bay of the Space Shuttle

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5. CONCLUSION

This paper details the development of the novel deployable origami baffle which has significant potential for the design of optical systems. By effectively reducing stray light while maintaining a lightweight and compact structure, this innovative design addresses critical challenges faced in various applications, from photography to satellites. The incorporation of Kresling origami principles not only enhances the baffle's compactness but also allows for adaptability to diverse system requirements, ensuring optimal performance across different operational scenarios.

The successful construction of multiple small-scale prototypes demonstrates the feasibility of this design approach and opens avenues for future research and development. As the demand for lightweight optical solutions continues to grow, the deployable origami baffle holds promise for a wide range of applications, paving the way for enhanced capabilities in optics and beyond. As the burgeoning space industry develops, origami is expected to play a large role in everything from solar panels, satellites, and habitats.

Future work will focus on analysis and simulation of the design, identifying materials that would still enable functionality while maintaining required stiffnesses. Resilient coatings will be crucial to both prevent stray light and to survive panel/crease interfaces. Tradeoffs of geometrical ratios, number of sides, form factor, etc. would need to be identified to make these useful for wider adpotion. Deployment mechanisms will need to be fleshed out and trade studies accomplished. Creation of a larger prototype with realistic optical properties will need to be tested to validate existing models and expected design parameters. Furthermore, additional exciting applications are expected of Kresling origami as designs are refined. By continuing to refine and optimize this innovative baffle design, it is hoped that deployable origami can contribute to the advancement of optical technologies that meet the evolving needs of scientific exploration and discovery.

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