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Design of Deployable Optical Space Arrays Based on a Thickened Origami Flasher Pattern

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ABSTRACT

Performance of space-based optics could be greatly enhanced by using deployable origami-based arrays, which can offer a large aperture size relative to their stowed volume when compared to traditional technology, thus improving imaging quality.

In this work, we select, develop, and adapt the origami flasher pattern to serve as the foundation for a deployable array that shows promise for meeting stringent optical requirements. We apply a novel thickness accommodation technique, improve stability by adjusting geometric characteristics of the pattern, and create an array of frames for housing optical elements in a co-planar configuration. By following the guidelines in this work, more efficient and powerful optical arrays can be developed.

INTRODUCTION

Spatial array mechanisms in the optical field typically require high flatness, precision, and repeatability that can be difficult to achieve in a deployable system. The objective of this work is to present the preliminary development of an origami flasher-based deployable mechanism design suitable for optical space arrays.

The family of origami flasher patterns has a high ratio of stowed-to-deployed-area and circularity when deployed. These attributes improve space efficiency when stored and increase aperture size, creating the potential for improved optical performance. While the flasher pattern has many benefits, it has several challenges that need to be addressed before being used in optical applications. The main challenges include non-rigid foldability, difficult thickness accommodations, and precision panel alignment.

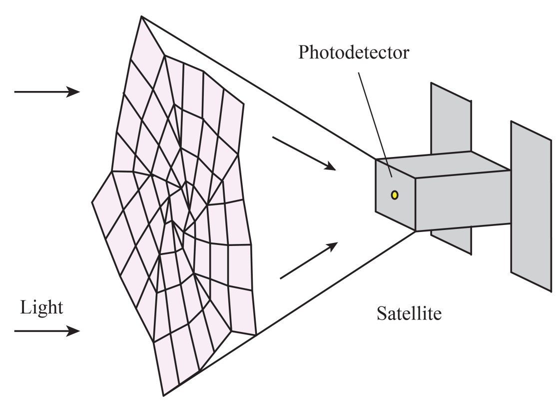

Figure 1: A LiDAR telescope concept is depicted with a deployable lens (flasher pattern). Captured light is directed toward a photodetector in the main satellite body.

If these challenges can be overcome, the resulting modified flasher could be effective in optical space missions (see Figure 1). In this work, we describe an addition to the tapered panel thickness accommodation technique,[1] introduce a method to minimize the negative effects of non-rigid foldability, and propose an approach for producing precision alignment in these arrays.

The flasher pattern has been proposed for various applications. Zirbel et al. designed a flasher with membrane hinges to be used as a solar array.[2] Wang and Santer[3] proposed a concept for a deployable reflector with finite thickness panels based on the origami flasher pattern. Bolanos et al. described an approach for selecting an origami pattern for a deployable space array.[4] Lang et al. solved the problem of non-rigid foldabilty in the flasher by placing a single cut along a sector, while still retaining one DOF.[5] Guang and Yang provided a design approach for a cut flasher with added thickness.[6] Kwok developed a geometry-based simulation framework for thick origami mechanisms comprised of mountain and valley folds.[7] Horvath detailed how various parameters modify a flasher's configuration and gave insight into how a flasher may be applied to an engineered system.[8] Bolanos analyzed several key parameters of the flasher pattern and describes the effects of modifying these parameters on several key outputs which are especially important in deployable origami space applications.[9] Arya et al. designed, fabricated, and analyzed a 10m flasher pattern for use as a starshade inner disk optical shield.[10]

These researchers have laid vital groundwork for applications of the flasher in precision environments. In this work, we design a flasher-based deployable array while considering stability and flatness and attempt to do that intrinsically so as to minimize the need for other devices to help minimize stowed volume.

FLASHER CONFIGURATION SELECTION

We selected a configuration of the flasher that would achieve good performance as a thickened, deployable array. Justifications for the rotational,

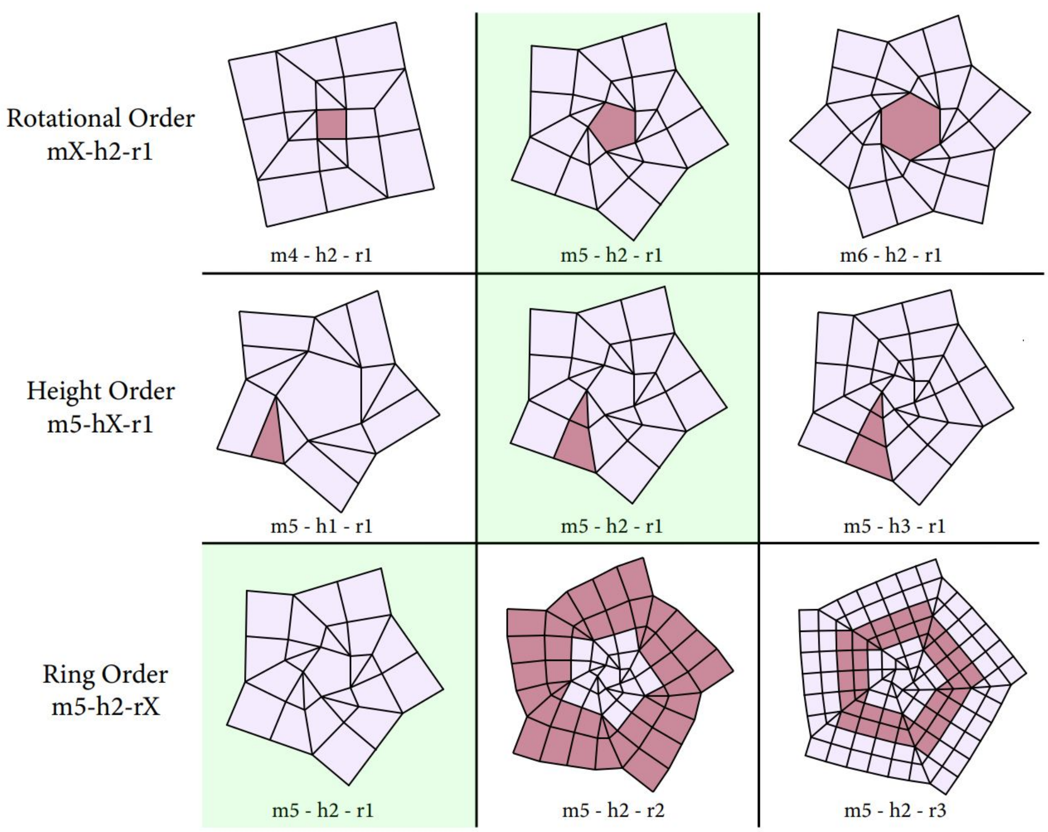

Figure 2: Several candidate origami flasher patterns with varying rotational, height, and ring orders are depicted. The pattern shaded in green, m5-h2-r1, was selected as the pattern for our deployable space array. Note that a standard dr value of 1.6 was used to generate the above patterns. The m5-h2-r3 pattern is an exception with a dr of 0.

height, and ring orders are discussed here. The *dr* parameter is defined as a characteristic separation between vertices that corresponds closely to the array thickness.[2] A *dr* parameter value of 1.6 was selected for the flasher pattern used in this project to obtain a sufficient aspect ratio for array stability. We selected a rotational order of five to produce a flasher that had good circularity, which has optical advantages. Additionally, this choice helped to decrease the angular displacement during deployment of the panels in each sector; the five-sided flasher has less angular displacement than a four-sided, but more than a six-sided. From prior work, we discovered that a four-sided pattern demands major angular displacement during deployment (too much to be counteracted by compliant joints) between rigid, non-bisected panels. In contrast, a six-sided pattern allows for much less angular deviation yet requires many more panels to be manufactured and aligned. Thus, the five-sided flasher is an advantageous pattern configuration in terms of balancing angular displacement and panel count. See Figure 2 for a visual of increasing panel count.

A height order of two was chosen because of its large deployment factor relative to a height order of one. A height order of three was not selected due to its increase in panel count and resulting complexity. The last pattern-determining parameter, the ring order, was selected to be one. This decision similarly reduces the panel count and complexity in the array. Furthermore, the error associated with hinged panels is kept small compared to a multi-ring flasher with compounding error due to slight misalignment of the hinges. This also significantly reduces the manufacturing load. The selected permutation is therefore a m5-h2-r1 flasher pattern as shown in Figure 2. This pattern is judged to be a good candidate for optical applications and is comparatively simple to manufacture.

THICKNESS ACCOMMODATION

To maximize stability and alignment capabilities of the array (which would produce a high performing optical array), we maximize the aspect ratio, based on the assumption that the thicker the panels, the higher the stability of the array. The aspect ratio of the array is defined as the diameter of the deployed circumscribed circle divided by the average thickness of the panels. The number of panels were limited under the assumption that more panels causes stabilization and alignment to become more challenging.

The tapered panel thickness accommodation technique was employed, as proposed by Tachi[11] as a basis for the thickness accommodation because of its ability to accommodate thickness in multiple directions at once and the protection it gives to the optical elements.[9] However, when applied to the flasher, it results in a zero-thickness portion at panels A1 and B1 (see Figure 3 for panel nomenclature), which is difficult to fabricate and reduces the stability of the array. An adjustment was needed for those panels. One possibility was to completely remove the corners of the triangles that taper to zero thickness. Another possibility was to remove some material from the surrounding panels to accommodate for the thickness of the A1 and B1. This idea nested the A1 and B1 panels into each other and into the surrounding panels. This adjustment is described in further detail in the following sections.

Panel A1

The smallest panel of the flasher pattern tapers to zero thickness along its hypotenuse and central-polygon-adjacent edges. This zero thickness poses a threat to the flasher's stability and functionality. To overcome this obstacle, we thickened the top side of the panel to stiffen the frame. This added material exists in the empty space above the center polygon in the stowed configuration, without removing any volume from panel B1. When thickened in this way, the A1 panel improved stability of the array and has the ability to house an optical element between its upper and lower halves.

Nesting of Panel B1 into Panel A2

The panel B1 faces a similar challenge to that of A1. However, this panel has no empty volume adjacent to it to utilize. To avoid removing material from the A1 panel (which already has minimal thickness), we thickened the panel outward into the neighboring quadrilateral panel, A2. Figure 4(a) shows extruding thickness to the central horizontal line between panels. Figure 4(b) shows the dimensions of the intrusion into panel A2 from the added thickness of T_1 to panel B1. The hinge line needs to remain intact if the kinematics are to be preserved, which creates an inset in panel A2. This is similar to the offset panel technique.[12] Variable T_2 can be determined knowing the stowed angle of the panel B1 zero-thickness line (θ_1) and the desired minimum thickness of panel B1 as

$$T_2 = \frac{T_1}{cos(\theta_1)} \quad (1)$$

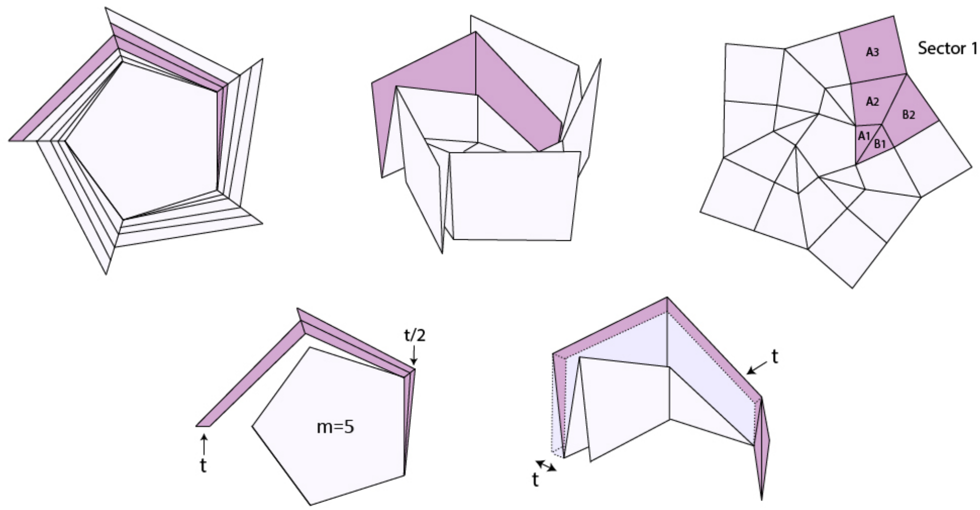

Figure 3: The m5-h2-r1 pattern is illustrated in stowed and deployed configurations. Top from left: The pattern's top view is shown. An isometric view of the paper-thin pattern is illustrated stowed. The flasher is deployed with one of five sectors highlighted and its panels labeled. On the bottom row, one sector of the five-sided pattern is featured to clarify how it stows with thickness added.

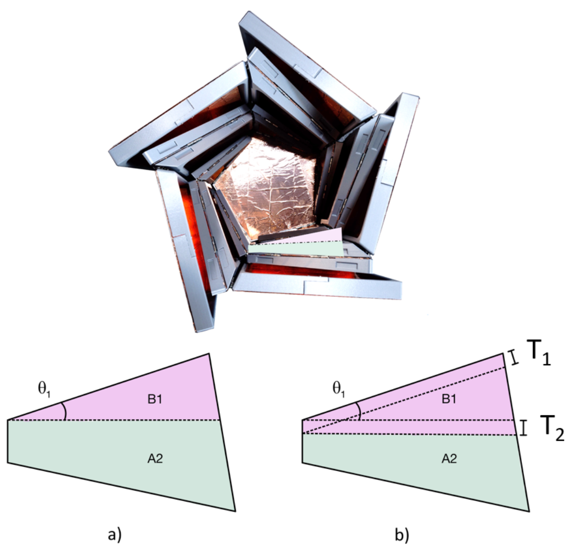

Figure 4: (a) Panels A2 (green) and B1 (magenta) are illustrated with B1 converging to zero thickness. (b) Panel B1 is nested into A2. An offset panel technique allows material to be taken from A2 and given to B1 while preserving the same hinge line.

FLATNESS (DEPLOYED CO-PLANARITY)

Placing optical elements onto panels created directly from the tapered panel technique would result in non-coplanar surfaces. We purpose to achieve coplanar optical elements by insetting these lenses in structural frames that have been modified by the offset panel technique and Tachi's tapered panel technique.[11] This is shown in Figure 5. The 5-2-1 flasher mechanism was designed in the stowed state to simplify the process of applying the tapered panel thickness accommodation to each panel (A1, A2, A3, B1, and B2). A version similar to the tapered panel thickness accommodation used by Arya[10] was applied between panels along major fold lines. Additionally, material in the shape of a wedge was added to the adjacent sides of panels A1 & B1, B1 & A2, A2 & B2, and B2 & A3 which provided a thick hard stop for adjacent panels to rest against at the appropriate angle (approx. 15 degrees) to achieve a single flat plane. Figure 6 highlights how these optical elements lie coplanar inside the tapered frames.

Figure 5: An angled view highlights the non-intuitive panel geometry formed as a result of implementing highly structured thickness accommodations. Thin copper wafers align throughout the array to form a coplanar surface.

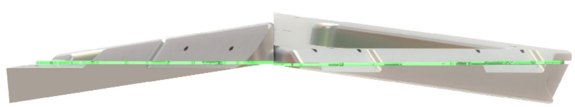

Figure 6: A coplanar region between two panels, A1 (left) and B1 (right), is highlighted in green.

To simplify the design process, we used triangular panels to create a new plane whereon the non-bisected quadrilateral panels would be formed. We reduced negative misalignment effects by splitting the difference between the slightly angled triangular panels. The non-bisected quadrilaterals were thickened from this new plane to create the panels referenced in this study. These panels have a slightly different footprint from the true triangular panels. This geometric imperfection is expected to add a small strain to the joints during the folding motion of the array.

Estimated Flatness

A physical measurement of the alignment between panels was estimated using a red-laser 3D scanner. The resulting surfaces and reference coordinate systems are shown in Figure 7. The Panels A1 and B1 were separated from the array and then scanned in an upright position. The angular misalignment between these panels is listed in Table 1. Panel A1 is the reference panel (assumed to have no misalignment). with the convention being to rotate about yaw, pitch, and then roll, all about the current axis. Performing these rotations resulted in a well-aligned panel in terms of angular misalignment. Since the alignment requirements for LiDAR-based optics are typically lower than other systems, a deviation around 0.2° is acceptable.

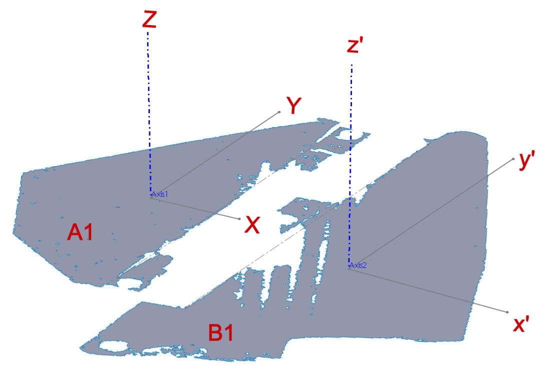

Figure 7: The surfaces and coordinate systems of panels A1 and B1, as measured using a red-laser 3D scanner, used to determine the relative misalignment are depicted.

Table 1: Rotational misalignment of panel B1 with respect to panel A1. To align with panel A1, panel B1 is rotated about yaw, pitch, then roll about its current axis.

Axis	Angle	Within Spec
Roll (about x"')	0.14°	Yes
Pitch (about y")	-1.95°	No
Yaw (about z')	0.2°	Yes

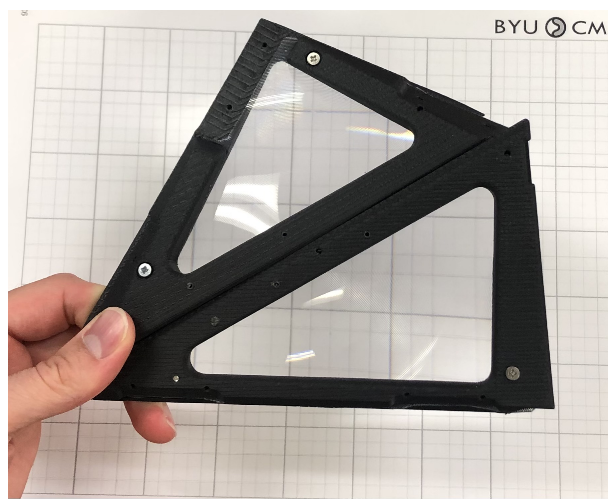

Figure 8: A fresnel lens is secured within the frames of panels A1 and B1.

FULL FLASHER REFLECTARRAY PROTOTYPE

To validate the concept presented here for a thick origami flasher pattern, we built and tested a 1 meter prototype. The prototype combines the specific permutation, thickness accommodation techniques, and coplanarity ideas discussed in sections 2, 3, & 4 into one array. This prototype is a direct result from the thickness accommodation techniques described in the previous section. For ease of manufacturing, we use thin copper wafers instead of optical elements like those shown in Fig. 8. The flasher panels were modeled and sliced for creation on a 3D printer.

This pattern is non-rigid-foldable, meaning that the transition from stowed to deployed states requires deformation of the panels or a disconnect of joints. We hypothesized that constraining the panels at the vertex (B1,A3) contributed most to binding during deployment. Therefore, to account for non-rigid-foldability in the pattern, rigid hinges were not placed near vertex (B1, A3).

Table 2: Output parameters of the final 5-2-1 flasher prototype.

Parameter	Final Value	Description
A	0.555 m^2	Total optical area of the array (panel frames not included)
dr	1.6	Variable That corresponds closely to the thickness of the array
d_{circ}	1.184 m	The circumscribed diameter of the deployed flasher
d_{ins}	0.842 m	The inscribed diameter of the deployed flasher
V	0.496 m x 0.476 m x 0.220 m	Stowed dimension (length x width x height)

The final flasher-based array with the thickness accommodation is shown in Fig. 9. The outputs of the final prototype flasher are listed in Table 2. The parameter A represents the total usable area through which light can pass. The dr parameter was previously noted as a number that corresponds closely to the thickness of the panels. Circles that circumscribe and inscribe the flasher pattern have diameters with values 1.184m and 0.842m respectively. The V parameter represents the volume that the flasher mechanism occupies when stowed (see the top image of Figure 9). A portion of this volume exists unused above the center polygon. This allows a different satellite component (such as a light detector) to be nested in this space. This is likely the thickest flasher made to date, with part thickness ranging from 0.5cm to 2.8 cm.

CONCLUSION

In this work, we demonstrated the use of a thick origami flasher pattern to develop a deployable array for use in an optical application. We performed thickness accommodation alterations to ensure that the array could completely stow and deploy. Most importantly, these thickness accommodations created a stable framework to align the zero thickness planes of all the panels.

We selected the 5-2-1 flasher pattern for this deployable lens application because it displayed the desirable characteristics of a lower panel count, a high deployed-to-stowed-area ratio, and a feasible degree of deployment resistance from its non-rigid-foldability. We chose a large thickness for the panels to maximize the stability and flatness of the array in the deployed state - features that are critically important for optical devices. We made a prototype of 3D printed materials. The flasher frames were modified to provide a coplanar section throughout the array onto which the optical elements can be affixed.

This work has several key contributions: (1) the development of a deployable array based on the flasher pattern with techniques to produce high stability, (2) an additional thickness accommodation technique applied to the flasher pattern and (3) an approach to produce a flat co-planar surface on an array with the tapered panel thickness accommodation.

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Figure 9: The flasher array's deployment process is illustrated with stowed, deploying, and fully deployed images. The full prototype unfolds from a small volume to span approximately 1 meter in diameter and provide 0.555m^2 of working optical area. Fresnel lenses may be replaced with thin copper plating (as shown in this image) for use as a reflectarray.

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