Origami-Inspired Mechanisms for Enhanced Efficiency and Reliability in CubeSat Solar Panels

Kevin Ong[1] and Annika Thomas[2]

***Abstract*—Foldable solar panels are a promising design for space applications, where minimizing stowed volume and maximizing deployed area are essential. Current solar panel systems are limited by their bulky stowage volume, complex deployment mechanisms, and vulnerability to mechanical failure during deployment or operation. This work explores origami- inspired folding patterns to enhance spatial efficiency along with their simple integrated deployment mechanisms suited for CubeSats. We evaluate structural integrity through CAD simulations and paper prototypes. By combining computational modeling and physical testing, the research aims to determine an optimal design that improves deployment efficiency and durability, contributing to more effective energy solutions for space environments. Thermal testing validates the design for survivability in space.**

I. INTRODUCTION

Traditional solar panels used in aerospace applications are limited by their rigid structure, weight, and size. This restricts the amount of power they can generate. Origami design enables compact stowage and precise, controlled deployment. Utilizing origami folding patterns creates lightweight, flexible panels that can fold into a small size for launch and expand once in orbit. This design maximizes surface area and reduces design complexity to improve deployment and solar collection.

Solar panels are typically designed as four rigid arrays that are either fixed or deployed using mechanical arms or hinges [1]. While effective, traditional deployment methods can be bulky and prone to mechanical failure, particularly in small satellites like CubeSats, where volume and mass constraints are critical. Additionally, many existing designs lack redundancy [2], meaning a single point of failure in the deployment system can compromise the entire mission.

In this work, we explore a range of origami folding techniques—including Miura, Kresling, and flasher patterns—to better understand which geometries are best suited for space-based solar panels. Each pattern is analyzed for its ability to minimize stowed volume while maximizing deployed surface area. These patterns have built-in deployment mechanisms that require minimal actuation due to many joints that move passively in one smooth motion.

To assess performance and durability, we analyze the structure of the design through both computational thermal simulations and physical models. CAD tools and paper-based origami prototypes are used to evaluate how each fold performs under simulated space conditions. Factors such as thickness, folding angles, and material properties are tested to understand how different configurations affect strength, flexibility, and deployment reliability. Thermal testing simulations are run to test for deformation, temperature concentration, and potential failure points in the design. This ensures the final design can endure the harsh thermal environment of space.

The contributions of this work are:

- Analyzing the Miura-ori, Flasher, and Kresling origami folding patterns and determining the most promising design that has the best ratio of stowed volume to surface area when deployed
- Developing solar panel designs using the Flasher model and making a physical prototype as well as with CAD in Onshape
- Validating thermal integrity through thermal analysis in SimScale and making sure that it's within the operational limits of common solar panel designs

The authors are with Monte Vista High School[1] and Massachusetts Institute of Technology Department of Aeronautics and Astronautics[2].

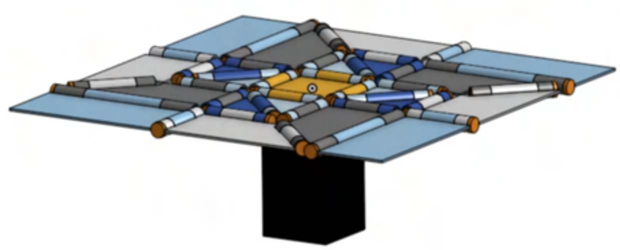


Fig. 1: Deployed configuration of origami-inspired foldable solar panel attached to 2U CubeSat

II. RELATED WORKS

A. Origami Folding Patterns

There are a few standard origami folding patterns that have aerospace applications due to their contractibility [3]. The Miura-ori is a tessellation of parallelograms that can expand and contract and is deployed by applying forces along the diagonals. The Flasher pattern has a rotational symmetric folding pattern and expands in a spiral. The Helix, specifically the Kresling, is a cylindrical structure that is collapsible through its axial miniaturization property. The Flasher pattern's high contractibility makes it ideal for solar panel application in space.

B. Origami in Aerospace

Origami is useful for its stowability, deployability, and reduced assembly [4]. This is important because aerospace systems are tightly constrained by volume and weight, and minimizing components and pre-deployment size directly reduces launch costs and mechanical failure risks. The Miura-ori pattern was the first application of origami in aerospace and was applied to the solar sail [3]. Origami bellows use the Kresling folding pattern to protect drill shafts on rovers while still being lightweight and compact [4]. Additionally, multi-stable origami bellows can be used for inflatable structures that can remain compact during launch and then lock into a fully expanded, rigid form once deployed, eliminating the need for complex active mechanisms [5]. This allows for increased space for long-duration human habitation or modular orbital infrastructure without increasing transportation costs. The Flasher fold can be applied to deployable parabolic antennas for RF reflectors and reflective optics [4]. Similarly, origami-based star shades use the Flasher folding pattern to block starlight and enable direct imaging of exoplanets [3].

C. Deployment Mechanisms

A Tensegrity structure is a lightweight, deployable structural system that can use strings or tubes as compression elements and tensioned cables. Furuya et al. introduce an approach to use inflatable tubes in Tensegrity structures which allows for compact stowage and simple deployment through inflation, avoiding complex mechanical systems. These structures offer high structural efficiency, modularity, and redundancy, making them promising for scalable space architectures [6]. Motors are another mechanism that can be used to pull two panels away from the center, causing a structure to open and flatten out [7]. This is useful for folding patterns like the Miura and Flasher as they deploy with one continuous motion.

D. Foldable Solar Panels

The SolarCube is an example of a foldable solar panel for 1U CubeSats and has a stowed-to-deployed ratio of 1:7 [2]. Its design utilizes a modified flasher pattern and uses Flexible Reinforced Electronic with Textile technology for reinforcement and weight reduction. Benchmark tests and Finite Element Method simulations were run to show its high energy output and stability through intense temperatures. The SolarCube is a TRL 3 at its current state, but is being developed further to reach TRL 4. Another origami-based portable solar panel system uses a Miura folding pattern ideal for emergency, remote, and mobile applications [7].

III. DESIGN APPROACH

A. Folding Patterns

Foldable solar panels on satellites require the ability to contract to fit the volume of a CubeSat while also being able to expand to maximize solar output when deployed in space. The Miura-ori, Flasher, and Kresling all have the ability to expand but in different ways. The Miura-ori stretches in one direction and flattens out in a plane. The Flasher opens in a spiral fashion. The Kresling is different from the others as it has a cylindrical shape and does not expand further than its confined form. The Flasher is most optimal and was chosen because its square geometries align with the CubeSats. These three designs are shown in Fig. 2.

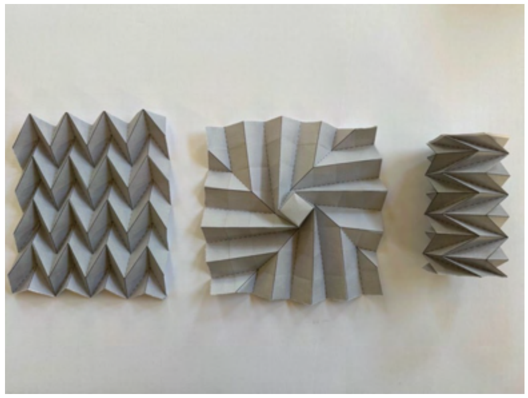


Fig. 2: From left to right: Miura-ori pattern, Flasher fold pattern, and Kresling fold pattern

B. Physical Prototype

Origami paper was used for experimentation to find a design that was simple yet still held the mechanical quality of the Flasher pattern. The original design collapses to a 1x1x1 cube which can fit a 1U CubeSat. The model is based on a 7x7 grid pattern which uses many unnecessary folds that adds thickness due to folding multiple layers of paper. The CubeSat dimensions are tightly confined so the 1U Flasher design was modified to a 3x3 grid which was much simpler and had fewer overlapping folds. Similarly, the 2U design minimized the number of folds but also expanded 1 unit out for a 1x1x2 rectangular prism shape.

The next phase of prototyping was adapting the paper to a material with thickness similar to that of solar panels. This was achieved with cardboard. To achieve folds, the cardboard was cut into panel pieces which were then connected by hinges made from straws, elastic string, and tape. These panels were created from the crease pattern of the paper designs. The 1U solar panel design used straws and string while the 2U design used tape. The straws could rotate almost a full 360 degrees while the tape limited rotation to 180 degrees. These designs are shown in Fig. 3 and Fig. 4.

(a) Stowed configuration

(b) Deployed configuration

Fig. 3: Foldable solar panel prototype for 1U CubeSat

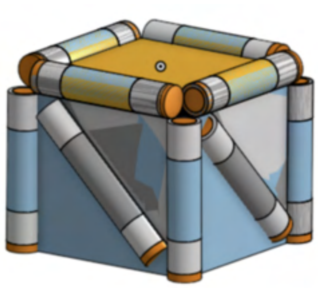
(a) Stowed configuration

(b) Deployed configuration

Fig. 4: Foldable solar panel prototype for 2U CubeSat

C. Computer Aided Design Model

The prototypes were adapted to CAD models for higher precision and a clear 3D visualization in Onshape [8]. The models include hinges with pins for axial rotation of the panels. Additionally, the parts are scaled accurately to fit the dimensions of the 1U and 2U CubeSat. The CAD model has a limitation of overlapping panels and hinges. This is due to the hinges being full cylinders and the panels being centered between the hinges. Future work will address these limitations. These models are a work in progress, but show the fundamental design in a clean way. Each color represents the different parts used. These models are shown in Fig. 5 and Fig. 6.



(a) Stowed configuration

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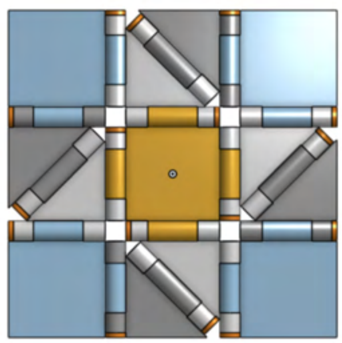
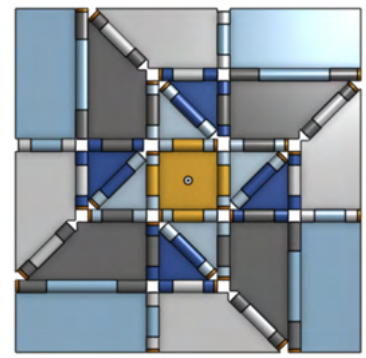
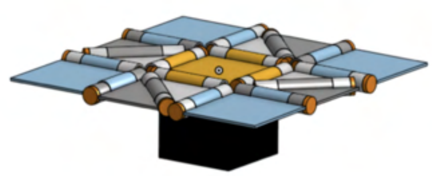


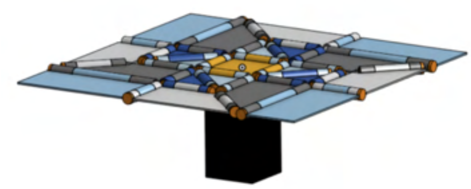
(b) Deployed configuration



(b) Deployed configuration



(c) Deployed configuration attached to CubeSat



(c) Deployed configuration attached to CubeSat

Fig. 5: Foldable solar panel CAD model for 1U CubeSat

Fig. 6: Foldable solar panel CAD model for 2U CubeSat

IV. RESULTS

A. Simulation Setup

We conduct a thermal analysis test in SimScale [9] and utilize the Heat Transfer simulation. For materials, the panels were set as silicon and the hinges and CubeSat were aluminum. The boundary conditions were surface heat fluxes; one applied to the top face and another to the bottom. The top had a heat flux value of 1361 W/m^2 and the bottom 400 W/m^2 to reflect solar flux and earth albedo. A mesh was created and then the simulation was run for 100 seconds. This process was repeated for both the 1U and 2U design models to see points of high thermal concentration and validate that they are within the operational temperature range of space rated solar panels.

B. Thermal Analysis Results

The results of the thermal analysis tests were found within the reasonable temperature values for survivability in space. The 1U and 2U design had a range of 20 $^{\circ}$C to 34 $^{\circ}$C. The heatmap is shown in Fig. 7 and Fig. 8. This is consistent with the operational range of the TurkSat's simulation regarding its solar panels which were between -40 $^{\circ}$C and 85 $^{\circ}$C [10]. The hottest parts are concentrated towards the outer edges of the panels while heat transfers into the rest of the CubeSat in the middle hence it being the coldest region.

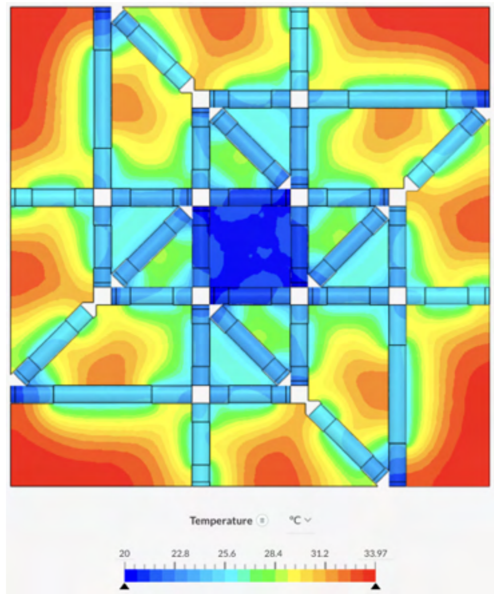


Fig. 7: Thermal stress analysis of foldable solar panel for 1U CubeSat

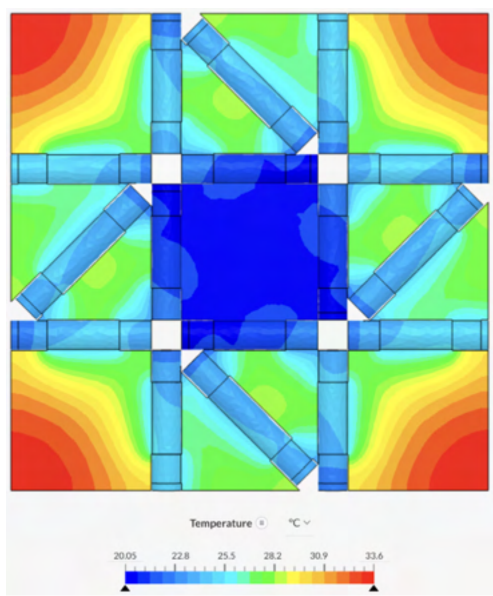


Fig. 8: Thermal stress analysis of foldable solar panel for 2U CubeSat

V. CONCLUSION

This work presents a Flasher-based foldable solar panel design for the 1U and 2U CubeSat. It outlines the design process of experimenting with origami patterns, prototyping, and CAD modeling. The final result is a working concept that increases the surface area of solar panels from the current state of designs. The next steps are integrating a deployment mechanism and refining CAD modeling to not have overlapping panels. This will enable production for a fully fleshed out prototype.

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