Compliant Mechanisms for Deployable Space Systems

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Compliant Mechanisms for Deployable Space Systems

Shannon A. Zirbel

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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The purpose of this research is to develop fundamentals of compliant mechanisms in deployable space systems. The scope was limited to creating methods for thick origami, developing compliant deployable solar arrays, and developing methods for stowing and deploying the arrays. The research on actuation methods was focused on a one-time deployment of the array. Concepts for both passive and active actuation were considered.

The primary objective of this work was to develop approaches to accommodate thickness in origami-based deployable arrays with a high ratio of deployed-to-stowed diameter. The HanaFlex design was derived from the origami flasher model and is developed as a deployable solar array for large arrays (150 kW or greater) and CubeSat arrays (60 W). The origami folding concept enables compact stowage of the array, which would be deployed from a hexagonal prism into a flat array with about a 10-times increase in deployed diameter as compared to stowed diameter. The work on the origami pattern for the solar array was also applied to the folding of 80-100 m² solar sails for two NASA CubeSat missions, NEA-Scout and Lunar Flashlight.

The CubeSat program is a promising avenue to put the solar array or solar sails into space for testing and proving their functionality. The deployable array concept is easily scalable, although application to CubeSats changes some of the design constraints. The thickness-to-diameter ratio is larger, making the issues of thickness more pronounced. Methods of actuation are also limited on CubeSats because of the rigorous size and weight constraints.

This dissertation also includes the development of a compact, self-deploying array based on a tapered map fold design. The tapered map fold was modified by applying an elastic membrane to one side of the array and adequately spacing the panels adjacent to valley folds. Through this approach, the array can be folded into a fully dense stowed volume. Potential applications for the array include a collapsible solar array for military or backpacking applications.

Additional compliant mechanism design was done in support of the HanaFlex array. This included a serpentine flexure to attach the array to the perimeter truss for deployment, and a bistable mechanism that may be used in the deployment of the array or sail.

Keywords: compliant mechanisms, origami-inspired design, deployable solar arrays
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Finally, I would be remiss if I did not acknowledge the impact of good people in my life: my parents whose encouragement and support have shaped who I am; friends and family who continue to believe in me and my dreams; and teachers and professors from grade school to university who saw potential in me and helped to develop it. I am indebted to you.

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CHAPTER 1. INTRODUCTION

This research develops the fundamentals of compliant mechanisms for their application to deployable space systems. The advantages of compliant mechanisms make them ideal for space applications, where lubrication-free and low weight mechanisms are essential. Examples of fundamental understanding that need to be developed include foldable thick systems and monolithic bistable systems capable of implementation in flight-approved materials. Other foundational work in the area of compliant space mechanisms includes identifying and developing space-compatible materials for compliant mechanisms, hinging panels with compliant mechanisms, joining materials, actuation of compliant space systems, application of compliant mechanism technologies in metals or other flight-approved materials, and bridging the fields of compliant mechanisms and traditional spacecraft design.

Compliant mechanisms perform their function through the elastic deflection of their members. Under this definition, origami-inspired design is usually classified as a compliant mechanism. This project will contribute to the knowledgebase on compliant space mechanisms, particularly through the design of the origami-inspired deployable array, HanaFlex, and the development of several building-block mechanisms.

HanaFlex is a new method for deployment from a compact folded form to a large array. One of the unique features of this model is that the height constraints of the stowed array do not limit the deployed diameter. Additional rings can be added to increase the deployed diameter while only minimally increasing the stowed diameter. Larger solar arrays may enable longer missions in space, manned missions to distant destinations, or clean energy sources for Earth. The novel folding design of the HanaFlex array introduces many new possibilities for space exploration.

The HanaFlex design was derived from the origami flasher model and is developed as a deployable solar array for large arrays (150 kW or greater) and CubeSat arrays (60 W).
The origami folding concept enables compact stowage of the array volume that would be deployed into a flat array with about 10 times increase in deployed diameter as compared to stowed diameter. Origami folding has been used in “sheet goods” for space, such as the Miura-ori fold [1,2]. Current deployable arrays typically accordion-fold. By introducing additional fold lines along other axes, we expect to maximize the stowed volume space within the medium-lift launch vehicle class.

The work on the origami pattern for the solar array was also applied to the folding of 80-100 m$^2$ solar sails for two NASA CubeSat missions, NEA-Scout and Lunar Flashlight. The CubeSat program is a very promising avenue to put the solar array or solar sails into space for testing and proving their functionality. The deployable array concept is easily scalable, although application to CubeSats does change some of the constraints on the design. The thickness-to-diameter ratio is larger, making the issues of thickness more pronounced. Because volume is very constrained on CubeSats, methods of actuation are also limited.

This dissertation also includes the development of a compact, self-deploying array based on the tapered map fold designed by Charles Hoberman [3]. The tapered map fold was modified by applying an elastic membrane to one side of the array and adequately spacing the panels adjacent to valley folds. Through this approach, the array can be folded into a fully dense volume when stowed. The panels are dimensioned to account for the panel thickness when folded, which otherwise would prevent the model from reaching a fully dense form. Potential applications for the array include a collapsible solar array, or other military or backpacking applications.

Some compliant mechanism design was done in support of the solar array design. This included a serpentine flexure to attach the array to the perimeter truss for deployment, and a bistable mechanism that may be used in the deployment of the array or sail. Compliant bistable mechanisms can also be used in space applications as switches, latches, or relays, thereby eliminating friction and improving the reliability and precision of those mechanical devices. Such mechanisms could be integrated into deployment systems as non-explosive release mechanisms.
1.1 Background and Literature Review

The work in this dissertation merges compliant mechanisms and origami-inspired design with traditional spacecraft design. Both fields of compliant mechanisms and origami-inspired design are replete with advantages that can be exploited with great benefit in space technology research areas.

1.1.1 Compliant Space Mechanisms

The advantages of compliant mechanisms include increased performance, reduced or eliminated assembly, no friction or wear, fewer parts, lower cost, and lower weight. These advantages make compliant mechanisms ideally suited for space or aerospace applications, where low weight and no lubrication are essential. A recent white paper on compliant space mechanisms [4] demonstrates that space applications are a large, mostly untapped field that will benefit from compliant mechanism technology.

Flexures were used in the wheels of the Mars Science Laboratory and Mars Exploration Rovers to provide some suspension. Flexures have also been used for precision instruments such as optics, and to compensate for different coefficients of thermal expansion in different materials [5]. A compliant hinge providing 90 degrees of rotation was recently developed [6].

Design and analysis tools for compliant mechanisms have advanced rapidly in the last 15 years, enabling the purposeful design of devices with flexibility. Flexible structures and mechanisms have frequently played a role in space exploration, in deployable booms, flexures for optics, etc. With the improved analytical tools, these areas can be expanded. Large deformations are possible and devices can be designed for repeatable motion or for infinite life.

1.1.2 Deployable Systems

One of the inherent benefits of compliant mechanisms is their reduced mass and volume compared to traditional mechanisms. Applications for mechanisms that are lightweight are
especially appealing to aerospace research where the payload mass determines the cost and size of the launch vehicle.

Compliant mechanisms are ideal for creating deployable systems. Deployment hinges and other deployable structures typically require multiple components, which increase weight, assembly, and wear. Compliant mechanism technology offers the potential to integrate these functions in fewer components with overall reduced mass and increased reliability.

Also, the proposed research is to develop new methods for deployment from a compact folded form to a large array (or other final form). For the solar array application, the desired final form is flat, but it is also possible to deploy into a concave or convex form as well (e.g., for satellite receivers) [7].

1.1.3 Rigid Origami

Origami-inspired folding of deployable systems can enable a compactly stowed volume during launch and flight that will be deployed into a much larger volume when the target location is reached. Origami models are generally created for near zero thickness material. Panel thickness is one of the main challenges of origami-inspired engineering design [8]. Rigid-foldable origami (also called rigid origami) defines those models that can still be folded when the facets are replaced with rigid panels and the creases are replaced with hinges [9]. The field of rigid-foldable origami is an active area of research and has many open problems.

Tachi has achieved rigid foldability with non-concurrent axes, where the axes are shifted to enable the model to fold, as shown in Figure 1.1a, or by reallocating material or removing material near the fold line, as shown in Figure 1.1b [10].

Trautz and Künstler [11] identified the hinge translations that occur when thickness is added to the model. Without other compensation, a degree-4 vertex (or a spherical mechanism) with thickness added must allow sliding along the rotational axes or hinge lines to compensate for the doubled number of constraints around each vertex and to enable the model to fold.

Hinge components are often added to the model to enable the folding of thick, rigid materials. Hoberman [3, 12, 13] has presented several concepts related to adding hinges to thick rigid origami to enable foldability. In his earlier work, tapered strips accounted for
Figure 1.1: Two approaches for enabling origami with thickness, from Tachi [10]: (a) The axis of rotation for the fold is shifted from the midline of the material to the material surface. (b) Material is removed near the fold line. In both (a) and (b), the dashed line represents the zero-thickness model.

Material thickness and ordered pleating enabled the thick sheets to collapse on themselves. In more recent work, the hinges do not lie in the same plane, so their axes do not intersect [13]. These offsets enable the mechanism to be rigid-foldable into a compact unit. Hoberman mechanisms were used by Faist and Wiens in 2010 in the design of deployable antennae and solar arrays [14].

The Miura-ori model is one of the landmark rigid-foldable deployable structures [1,2]. The Miura-ori fold pattern is folded like a map fold, but with angled folds along one dimension (see Figure 1.2). The resulting package is mostly synchronous, but has a slight lateral offset. As the angle increases, the package opens more synchronously (with $x$ and $y$ opening almost at the same time). As the angle $\alpha$ decreases, the package opens with less synchrony. The trivial $\alpha = 0^\circ$ case is the map-fold, where the model unfolds entirely in one direction before the perpendicular direction can unfold.

Sternberg [15] presented several concepts showing collapsible folds in origami. He briefly addresses the problem of material thickness, but he particularly addresses the problem of collapsibility (or conversely, deployability). He suggests that introducing slight asymmetry
Figure 1.2: Crease pattern for the Miura-ori fold, based on [1,2].

to the model allows the collapse to occur. While the symmetry provides the rigidity in the model, a slight skew in the pattern will allow compressive and tensile forces to be “released”, thus enabling the model to collapse.

Guest and Pellegrino [16] presented a modeling technique for wrapping thin membranes around a central hub. They showed that the model can be adjusted for thickness by increasing the panel dimensions as the distance from the center of the model increases and that the six-sided flasher model can be “inextensional” (i.e., the panels are unstretched) in its flat and folded states, but not necessarily in transition between the two.

Nojima [7] also presented several radially deployable origami models, many of which are generalizations of the Guest/Pellegrino winding membrane structure and are related closely to the model used in this work. Guest and De Focatiis also published work on deployable membranes which were achieved by combining several corrugated patterns [17].

The patterns described by Guest and Pellegrino [16] and Nojima [7] allow the folding of an arbitrarily large, roughly circular region into a polygonal cylinder (or cone, as in some of Nojima’s structures), whose diameter in the folded form is much smaller than that of the unfolded surface. A notable property of these structures is that for a given central polygon diameter, the diameter of the folded cylinder stays roughly fixed as the diameter is increased, while the length of the cylinder increases roughly linearly with the diameter of the unfolded
pattern. This scaling factor can be reduced by increasing the rotational order of symmetry of the pattern, or increasing the number of sides of the central polygon.

This “winding membrane” family of patterns has been independently (re)discovered many times by researchers and artists alike. Within the world of origami, Shafer and Palmer, inspired by unpublished work of David Huffman (personal communication, ca. 2005), developed a concept that has come to be called a “flasher” [18–20]. A notable innovation of the Shafer/Palmer flasher was the addition of multiple folds along mirror planes normal to the cylindrical axis, which allows the structure to maintain roughly constant diameter and roughly constant cylindrical length as the diameter of the unfolded pattern increases, albeit at the cost of a now quadratic, rather than linear, increase in the number of layers wrapping around the cylinder. This property of roughly constant size as the unfolded diameter is scaled makes the “flasher” family of structures particularly suitable for deployable structures, and it is the basis of the structure investigated here.

1.1.4 Compliant Bistable Release Mechanisms

Release mechanisms have been developed in response to the need to anchor deployables to the spacecraft body for launch and flight, and then to be released on electrical command. Pyromechanical release devices [21–24] are the most common release mechanisms in aerospace applications. They have a fast response and are well understood, but are costly, one-shot devices, that exhibit large pyro-shock loads.

Release mechanisms can be divided into pyromechanisms and non-explosive release mechanisms. Pyromechanisms can be further subdivided into (1) separation devices (which carry heavy loads, to be released on command), (2) cutters, and (3) pin pullers. A pyromechanism is characterized by pyro-shock, which can be from 1000-3000 $g$’s for small pyros, and up to 20,000 $g$’s for large pyros. “The load is applied so fast that the stresses at the point of application do not reach the mass of the structural element before the next increment of load is applied; i.e., the loading is being applied faster than the material can respond, and a shock wave is induced in the material” [21].

Non-explosive release mechanisms are characteristically slow, have lower force output, and are difficult to time. However, they do not have the high shock loads associated
Figure 1.3: The force-deflection response for a typical bistable mechanism. An optional preload stabilizes the mechanism for lower force inputs.

with pyromechanisms. Burn-wire mechanisms, paraffin actuators, and shape-memory metal release mechanisms all have less shock, but have slower actuation times, are more complex, and less robust than pyromechanisms.

Bistable mechanisms are a potential alternative to pyromechanical release devices. Bistable mechanisms are flexible devices with two stable equilibrium positions. These mechanisms take advantage of stable minimum-energy points in their geometrically nonlinear elastic energy curves. Compliant bistable mechanisms are specifically engineered so the energy stored in the deflected mechanism can be quickly released when the device is actuated.

Bistable mechanisms have an established history especially in micro devices [25]. Their application to macro devices, particularly in metals, and for space applications is still relatively novel. The exception is the Bearing Active Preload System (BAPS) [26,27]. In this bearing ring, bistable mechanisms are used to apply a high preload during launch and a low preload during flight. The bistable mechanisms are SMA-actuated, but must be manually reset in the current design.

1.2 Dissertation Organization

The research is organized into chapters. Chapter 2 introduces HanaFlex as a potential design for a large, deployable solar array. Chapter 3 presents the method for accommodating thickness in the origami-inspired design. Chapter 4 details the application of that same folding pattern to solar sails. Chapter 5 contains the modification of the HanaFlex design
for the CubeSat size scale. Chapter 6 presents the research on methods of actuation for deploying the solar array at both the 25-meter and CubeSat size scales. Chapter 7 includes the development of a compact, self-deploying array based on the tapered map fold. Chapter 8 discusses the design of the compliant bistable mechanism in metallic glass (Vitreloy 1). And finally, Chapter 9 contains the concluding remarks on the dissertation work as a whole.
CHAPTER 2. HANAFLEX: A LARGE SOLAR ARRAY FOR SPACE APPLICATIONS

2.1 Introduction

As we continue to advance space exploration, there is a need for solar arrays that enable greater energy generation. We have developed a large solar array than can be compactly stowed for launch to fit within a medium-lift launch vehicle, as classified by NASA [28]. Launches are constrained in size and weight. It is more expensive to launch heavier or larger vehicles. The cost to reach low earth orbit (LEO) is approximately 22,000 USD per kg (10,000 USD per pound). Origami-inspired folding of deployable systems can enable a compactly stowed volume during launch and flight that will be deployed into a much larger volume when the target location is reached.

This paper discusses the origami flasher design as a solar array for large arrays (150 kW or greater). The origami folding concept enables compact stowage of the array volume that would be deployed into a flat array with about 10 times increase in deployed diameter as compared to stowed diameter. Origami folding has been used in “sheet goods” for space, such as the Miura-ori fold [1,2]. Current deployable arrays typically accordion-fold. By introducing additional fold lines along other axes, we expect to maximize the stowed volume space within the medium-lift launch vehicle class.

The design, shown as a 1/20th-scale prototype in Figure 2.1, is called the HanaFlex. “Hana” is Japanese for flower and “flex” refers to the flexible substrate to which the solar panels are affixed. HanaFlex is an array of solar panels that wrap around the outside of the spacecraft for launch and then deploy into a 25 meter array. It is designed to fit inside of an Atlas V rocket for launch. The Atlas V rocket is capable of lifting up to 18,810 kg to low earth orbit (LEO), classifying it as a medium lift launch vehicle. Previous work derived the HanaFlex form from origami and developed an approach to accommodate for the thickness
Figure 2.1: Partially opened model of the HanaFlex array and truss. With a 1.25 m diameter, this is a 1/20th scale model of the large array.

of the panels [29]. This paper investigates the HanaFlex as a solar array with a 25-meter deployed diameter.

2.2 Background

Spacecraft typically rely on a combination of solar arrays and nuclear energy for electricity. Chemical and ion propulsion systems are also commonly used. Larger solar arrays can enable longer missions, manned mission to Mars or other distant destinations, or can even be used as an alternative energy source for Earth. For missions outside of Earth’s orbit, relying more heavily on solar arrays will greatly reduce the chemical propellant mass, which savings can then be translated into a larger payload or increased lifetime [30–32].

If the solar array is used to provide energy for humans to live while they are traveling in space, then they need to be capable of generating enough electricity for the systems required for maintaining human life. The arrays on the International Space Station generate 75-90 kW; therefore, the expected 150 kW from the HanaFlex would be sufficient to maintain human life for long distance missions.
The Voyager spacecraft are NASA’s longest running missions to date. Voyager I and II were launched in 1977 and are approaching the edge of the solar system. However, because they are powered by nuclear energy, their missions will end by 2020 when their power source is depleted. With large solar arrays, we open up the possibility of designing a mission with a lifetime of 50 or 100 years.

Conventional planar arrays consist of a series of rectangular segments that accordion-fold for launch [33–37]. Because of the volume constraints for launch-vehicle payloads, the size of the rectangular segments are limited. With a more complex folding pattern, we can maximize the available volume in the launch vehicle.

ATK Space Systems, Inc. has developed an array called UltraFlex that is comprised of several triangular panels which fold up rather like a Japanese fan. They are currently developing a large-scale version called MegaFlex, which would be capable of generating up to 400 kW of power. ATK has stated that the stowed volume of the UltraFlex occupies “a triangular space that is approximately 20% the stowed volume of conventional planar arrays, which enables spacecraft to maximize launch volume for critical payloads” [38].

There are advantages to having larger segments in the array. This would simplify wiring and fewer fold lines would reduce the likelihood of wire damage across fold lines. However, for getting it into space, the HanaFlex, with its multiple segments, would also have advantages, including efficient use of stowed volume space and a larger deployed area. There are many challenges for large solar arrays, but HanaFlex is one possible solution that addresses many of those challenges.

2.3 HanaFlex

HanaFlex is a new method for deployment from a compact folded form to a large array [29]. For the solar array application, the desired final form is flat, but it may also be possible to deploy into a concave or convex form as well (e.g., for satellite receivers) [7, 39, 40]. The folding design is based on the origami flasher model [20]. In origami, paper is usually assumed to have zero thickness, which is a close enough approximation for origami folding patterns to work. But when folding an array of solar panels, we needed to modify the folding pattern to accommodate for thickness and to ensure the panels would not flex [29]. Figure 2.2a shows
Figure 2.2: (a) The original origami crease pattern. (b) The modified crease pattern. The piecewise curvature of the lines effectively gives the panels more room between subsequent layers when the array is folded.

the original origami crease pattern, and the modified crease pattern is shown in Figure 2.2b. The piecewise curvature of the lines gives the panels more room between subsequent layers when the array is folded. As the panel thickness increases, the piecewise curvature becomes more pronounced, as can be seen in Chapter 3, Figure 3.4.

2.3.1 Design Specifications

NASA has specified several criteria for the design of large solar arrays (generating 150-300 kW of power) [41–43]:

- Deployed stiffness > 0.1 Hz
- Deployed strength > 0.2 g (all directions)
- Stowed volume specific power > 25-40 kW/m$^3$ at beginning of life (BOL)
- Mass specific power > 120 W/kg BOL
- Deployment reliability > 0.999
- Lifetime > 5 yrs
2.3.2 Design

One of the unique features of this model is that the height constraints of the stowed array do not limit the deployed diameter. Additional rings can be added to increase the deployed diameter while only minimally increasing the stowed diameter, as indicated in Figure 2.3. This feature sets it apart from other designs that are currently published. The Garolite panels represent areas where the solar cells would be affixed to the flexible substrate [44]. This would be similar to the photovoltaic blankets used in UltraFlex [38]. The stowed diameter of the array is almost one-tenth the deployed diameter.

HanaFlex is designed to wrap around the spacecraft. As we stow the array for launch, the panels rotate so they come up vertical against the side of the spacecraft. Foam spacers (or some other cushioning material) would be incorporated into the array to protect the solar cells from damage as they fold.

The following parameters describe the design shown in Figure 2.2b:

- Height of folded form = 4 m
- Crease pattern incircle = 30 m
- Maximum diameter (circumcircle) of folded form = 3.72 m
• Maximum width of any panel = 1.96 m

• Circumcircle of central polygon = 3.32 m

• Maximum spacing of any two vertices (thickness accommodation) = 4 cm

We obtain an effective flux of 300 W/m$^2$ by reducing the solar flux (1366 W/m$^2$) by a 75% “packing factor” of solar cells on the surface of the array and assuming 30% cell efficiency. For a 500 m$^2$ array, we estimate our design would have BOL performance of 150 kW for the effective flux.

The density of photovoltaic blankets is 1281.6 kg/m$^3$. This includes the mass of the photovoltaics. For blanket thickness of 0.75 mm, the areal density is about 1 kg/m$^2$. These values apply to photovoltaic blankets in general; we have assumed these as representative values for our design.

2.3.3 Deployment

We have designed the array to be deployed by a perimeter truss such as Northrup Grumman’s Astromesh. The research on deployment methods for the array were studied in previous work [45]. Astromesh has motors incorporated into the design at the geared hinges to open the truss. Because it will be deployed in a 0g environment (i.e. space), the weight of the array will not provide resistance to deployment, and any rotational inertia will actually help to deploy the array. Further, there is no “joint stiffness” in the hinges (or folds) of the array that would impede deployment. Therefore, the Astromesh is expected to provide sufficient actuation in its current configuration to deploy HanaFlex.

2.4 Analysis

The current work is primarily focused on the following four design specifications: deployed stiffness, deployed strength, stowed volume specific power, and mass specific power.
2.4.1 Deployed Stiffness

The PV blanket or folded substrate is attached directly to the perimeter truss. The substrate needs adequate tension to avoid spurious low-frequency modes. The first modal frequency needs to be greater than 0.1 Hz to meet the design specification. We can calculate minimum stiffness needed in the substrate from the following equation for a circular membrane [46]:

\[ f_{ij} = \frac{\lambda_{ij}}{2} \sqrt{\frac{S}{\gamma A}} \]  

(2.1)

where \( f_{ij} \) is the natural frequency in hertz; \( \lambda \) is a non dimensional frequency parameter related to the mode number (and is given in a table in [46]); \( S \) is the tension per unit length of edge; \( \gamma \) is the mass per unit area of membrane; and \( A \) is the area of membrane. For the first mode, \( \lambda = 1.357 \).

For the natural frequency, \( f_{ij} \), to be greater than 0.1 Hz:

\[
S = \left[ \frac{f_{ij}(2)}{1.357} \right]^2 \gamma A
\]
\[
= \left[ \frac{(0.1 \text{ Hz})(2)}{1.357} \right]^2 (1 \text{ kg/m}^2)(500 \text{ m}^2)
\]
\[
= 10.86 \text{ N/m}
\]

This value of \( S \) represents the minimum tension per unit length of edge to keep the deployed frequency above 0.1 Hz. Therefore, the tensile stress in the substrate must be greater than 14.5 kPa.

2.4.2 Deployed Strength

Material properties for the PV blankets was estimated based on typical woven fiberglass meshes. We have assumed a tensile strength of 200 MPa, an elastic modulus of 14 GPa, and a Poisson’s ratio of 0.4. For a simply supported circular plate subjected to a uniform
acceleration of 0.2 g, the following equations yield the stress in the plate [47]:

\[
\frac{a \ m \ R^4}{A \ E \ t^4} = K_1 \frac{y}{t} + K_2 \frac{y^3}{t^3}
\]

(2.2)

\[
\frac{\sigma \ R^2}{E \ t^2} = K_3 \frac{y}{t} + K_4 \frac{y^2}{t^2}
\]

(2.3)

where \(a\) is the applied acceleration; \(m\) is the mass of the array; \(R\) is the radius; \(A\) is the area of the deployed array; \(E\) is the elastic modulus; \(t\) is the blanket thickness; \(y\) is the maximum deflection; and \(K_i\) are constants based on material properties and edge conditions. For a simply supported plate:

\[
K_1 = \frac{1.016}{1 - \nu} \quad K_2 = 0.376
\]

\[
K_3 = \frac{1.238}{1 - \nu} \quad K_4 = 0.294
\]

By solving Eqn. 2.2 for \(y\), Eqn. 2.3 can be solved for the stress in the substrate. For the HanaFlex values introduced previously, the stress in the substrate is 1.44 MPa. This is well under the material tensile strength of 200 MPa, giving a healthy safety factor for the deployed strength requirement.

### 2.4.3 Stowed Volume Specific Power

The stowed volume of HanaFlex can be calculated by the following equation for a hexagonal prism with a hollow center:

\[
V_{shell} = \frac{3\sqrt{3}}{2} (a_{out}^2 - a_{in}^2) \ h
\]

(2.4)

where \(a\) is the panel width and \(h\) is the panel height. Because the interior space is occupied by the satellite, we exclude that volume. For \(a_{out} = 1.96 \ m\), \(a_{in} = 1.6 \ m\), and \(h = 4 \ m\), \(V_{shell} = 11.28 \ m^3\). This gives a power-to-volume ratio of 13.3 kW/m\(^3\), which does not meet the design specification of 25-40 kW/m\(^3\). However, the modified origami crease pattern accommodates up to 4 cm of spacing between vertices in the folded form, which is related to the panel
thickness. Because the photovoltaic blankets are much thinner than this specification, the stowed volume may be decreased substantially by reducing the vertex spacing for the modified origami crease pattern on which the design is based.

2.4.4 Mass Specific Power

To determine the mass specific power, we use the area density of the photovoltaic blanket to estimate the mass of the array. For an area density of 1 kg/m$^2$, the blanket mass is approximately 500 kg. Therefore, the ratio of power to mass is 300 W/kg, which is well above the design specification of 120 W/kg.

2.5 Discussion

The large ratio of deployed-to-stowed diameter is the primary benefit of the design, in that we can deploy a much larger array without increasing the launch vehicle class. A challenge that comes with the origami-inspired design is that the folding pattern requires that the panels be much more segmented, as compared to the large rectangles on the space station, which may introduce some limitations in the electrical connections of the PV cells. The design could potentially require more wiring, which increases weight, complexity, and failure modes.

We have demonstrated the deployability with the prototype. The deployment is smooth and almost synchronous, with no evidence of binding. With adequate joint stiffness, the deployment would be fully synchronous.

Resettability is much more challenging, but if we can make it retractable in space, then collisions with large meteoroids or other space debris would be avoidable [48,49]. There may be other advantages to retracting the array. The primary challenge is that, once it’s in a flat state, all the folds—which are really joints—become change-point mechanisms. The substrate would have to incorporate a device to bias the joint in the correct direction so it would fold up correctly. Once it starts, though, it does fold up easily. One unknown is the effect that wiring has on the folding motion.
Solar arrays for space applications are constrained by the size of the launch vehicle. To illustrate, the outer edge of the triangular panels of UltraFlex will be limited by the height of the payload volume in the launch vehicle. The design cannot simply be magnified in size to increase power generation. Whereas, because we have this more segmented design, we can add multiple rings to our array and thus continue to increase the deployed diameter without increasing the stowed height, so long as the stowed diameter fits within the payload envelope. It remains to find the optimized number and size of segments in the array.

Another concern about the wiring is the weight that the wires will add to the array. Launching one large array is still likely to be more cost-effective than launching several winglets in separate launches, as was done for the ISS.

As deployment is the highest perceived project risk, this needs to be tested with gravity off-loading on a final prototype. Also, a prototype needs to be made with the final material selection, with the PV cells fully wired, to demonstrate the functionality of the design. Although we have anticipated using crystalline PV cells in the design, flexible thin film photovoltaics may be an option worth considering. Although the efficiency is less than the single crystal silicon cells (18% compared to about 30%), the tradeoffs may be worth it [50,51]. Thin-film photovoltaics would require less protection from flexing and would likely weigh less overall. At some point, there is an optimal balance between efficiency and reduced weight. There is also the possibility of covering more of the substrate surface with thin-film PVs.

2.6 Applications

If we can generate more energy, then what missions can we accomplish? One potential application would be manned missions to Mars or some farther distance. If you are generating more energy, then you can support the life that is on the craft. The ISS is generating energy to support life, but very little is needed for propulsion since it is in orbit. Manned missions will require more energy than what is currently available.

Solar Electric Propulsion (SEP) is one way to use these large solar arrays for manned missions. SEP uses electricity from the solar panels to create ions, which are propelled through and out of the spacecraft, giving it the thrust to navigate through space [31]. For
this to be viable for our design, where the array encases the spacecraft, the nozzle through which the ion stream exits the craft would need to be deployed and gimballed away from the craft.

Another application is enabling longer missions. The longest missions right now are the Voyager spacecraft, and they are approaching 37 years in space. They are primarily nuclear powered, but their power source is going to run out in about five years. The problem with using exclusively solar energy for long-distance missions is that you would not be able to generate as much energy as you move further away from the sun. But an option may be to use solar energy for as long as is reasonable, and then switch over to nuclear energy to continue the mission.

An intriguing application for large solar arrays is to use them as a clean energy source for Earth (or for a Mars colony, one day). The theory for Solar Power Satellites (SPS) was researched and evaluated beginning in the 1980s [34, 52–54]. The solar cells on the array would generate electricity, which would then be transmitted to earth as a microwave beam of low power density [55, 56]. On Earth, the microwave energy could then be reconverted into electricity [57].

2.7 Conclusion

The novel folding design of the HanaFlex introduces many new possibilities for space exploration and, perhaps more importantly, for benefitting life on Earth. Ways that HanaFlex could have a positive impact on our daily lives would be by directing energy to Earth as a clean energy source, or perhaps using that same pattern for solar arrays on Earth. Less obvious are the spin-off technologies that may come from the development of this array. Space exploration enhances our technological capabilities and helps us progress as a society.
CHAPTER 3. ACCOMMODATING THICKNESS IN ORIGAMI-BASED DEPLOYABLE ARRAYS

3.1 Introduction

The purpose of this research is to develop deployment systems that unfold from a compact, folded form to a large array. The objective of this paper is to show the development of a mathematical model for creating rigid-foldable (and deployable) arrays from materials with finite thickness, and to demonstrate this through the design, modeling, and testing of a deployable system inspired by an origami flasher model, shown in Figure 3.1. Further work will include methods for actuating the deployment. This work is motivated by the need for compactly folded solar arrays for space applications. Maximizing the ratio of deployed-to-stowed diameter enables large solar arrays to be launched in their compact, folded configuration and then deployed in space to a much larger surface area. For our objectives, a design with synchronous deployment was desired to simplify actuation and deployment.

Deployment from a compact form to a final flat state can be achieved through origami-inspired folding of panels. There are many models capable of this motion when folded in paper or other materials with negligible thickness; however, when the application requires the folding of thick, rigid panels, material thickness can inhibit the folding motion. To be rigid-foldable, the panels must not be required to flex to attain the final folded form.

This chapter describes the approach for modifying the design of an origami six-sided flasher model to accommodate material thickness. This work builds on existing models to present a unique design that is rigid-foldable through two different methods. In the first method, the panels are allowed to flex along their diagonals. In the second method, the

\footnote{The content of this chapter was published in 2013 under the same title in ASME Journal of Mechanical Design, vol. 135, no. 11. The paper contains the full description of the mathematical model created by Robert Lang, which is omitted here.}
panels are affixed to a flexible membrane with discrete gap spacing between the panels. Both folding solutions enable the model to be rigid-foldable.

For the solar array application, it is assumed that crystalline silicon solar cells will be used, as they have the most established cell technology. Because the cells themselves are brittle, an array of these cells can be folded only if the membrane to which they are attached can be folded without requiring the panels (or solar cells) to flex.

### 3.2 Mathematical Model

Mathematical models of origami can prove useful in design and in facilitating the modification of crease patterns to accommodate material thickness. Such a model is proposed and developed for a thickness-accommodating flasher in [29]. A brief review of this model is included here.

In a zero-thickness model of a winding membrane pattern, the layers of the folded form are assumed to be coplanar. For a thickness-accommodating model, the layers must be slightly separated from one another to accommodate the thickness of the individual panels. Guest and Pellegrino suggested a radial logarithmic separation of the layers in the folded form [16]. This results in a piecewise linear curvature in the crease pattern, as shown in Figure 3.2 and Figure 3.3. The grey diagonal folds in Figure 3.3b are added to the crease
Figure 3.2: Comparison of (a) ideal and (b) thickness-accommodating winding membrane from Guest and Pellegrino [16].

Figure 3.3: The six-sided flasher model. (a) Model assuming zero-thickness. (b) Crease pattern for the model assuming finite thickness, with additional diagonal folds included to enable rigid-foldability.

Pattern to enable rigid-foldability of the model. Because a panel is defined by its vertices, the mathematical model [29] defines a discrete spacing between vertices that are physically adjacent. The results of the mathematical model are visually summarized in Figure 3.4.

We have created a Mathematica 8 notebook that sets up the constraints for a general flasher and solves for vertex coordinates for both the crease pattern and folded form. (It is available for download [58].) Figure 3.4 shows several wire-frame views of the crease pattern and folded form for $m = 6$, $h = 2$, $r = 2$, and $\delta = 0.1$, where $m$ is the rotational order of the pattern (or the number of sides of the central polygon), $h$ is the height order (or the number of axial bends between the bottom and top of the folded cylinder), $r$ is
Figure 3.4: A thickness-accommodating flasher \((m = 6, h = 2, r = 2, \delta = 0.1)\). Top row, l–r: crease pattern, single sector; folded form, single sector; folded form, side view. Bottom row, l–r: full crease pattern; full folded form; top view, folded form.

the number of rings in the pattern, and \(\delta\) is the specified spacing between vertices. These parameters are also defined in Figure 3.5. We have used the Mathematica notebook to solve for several thickness-accommodating flasher patterns and have built and tested physical models of several, including a design for application as a deployable solar array. These are described in the following sections.

3.3 Physical Model

The mathematical model defines the panel and hinge geometry that accommodates thickness in the folded configuration. Additional practical modifications are required to fabricate and test physical instantiations of the deployable system.

In this work, we explored two options for creating the rigid-foldable origami model: (1) allow the panels to fold along their diagonals (i.e. the model is entirely triangulated), or (2) apply a membrane backing to the entire model with specified widths at the fold-lines.
Figure 3.5: The parameters for defining the mathematical model are: (a) rotational order, \( m \), which is the number of sectors around the central polygon, (b) height order, \( h \), which is the number of axial bends between the bottom and top of the folded cylinder, and (c) number of rings, \( r \).

Both approaches rely on the mathematical model to accommodate panel thickness when folded. Option (1) also includes the grey diagonal folds from the mathematical model to enable rigid-foldability. Option (2) is motivated by the desire to keep the panels as large as possible to maximize the surface area to which solar cells may be affixed. In this approach, spacing between the quadrilateral panels at valley folds enables rigid-foldability.

Option (1) allows the panels to fold along their diagonals, shown in grey in Figure 3.3b. These additional folds concentrate the “flexing” that occurs in the panels during the folding process to be along these new hinge lines. The rotation at the diagonals was observed to be less than 5 degrees (a conservative estimate based on observation of actuated physical models), if all sides are actuated (folded) simultaneously.

The model is highly over-constrained. This can be seen in the Grübler-Kutzbach mobility equation for spatial mechanisms, which yields -36 degrees of freedom for the model shown in Figure 3.6.

Option (2) requires finding the optimal gap size to enable rigid foldability while maximizing panel surface area, shown in Figure 3.7. The membrane simulates the folding of near-zero thickness material, but with extra material allowances given in the gaps between the thick rigid panels to make up for the thickness of the panels. In Option (2), the distorted
Figure 3.6: The six-sided flasher \((m = 6, h = 3, r = 1)\) is rigid-foldable when additional fold-lines are added to the model along the diagonals of each panel. (a) The model in its deployed configuration. (b) The model in its stowed configuration. The valley folds are marked by the bold black lines.

Figure 3.7: The gap width was adjusted at fold-lines to enable rigid folding of the model on a membrane backing. In this model, \(m = 6, h = 3, r = 1\).

crease pattern from the mathematical model is still relied on to accommodate thickness in the folded form.
Figure 3.8: The folds of the membrane model are illustrated with the panels in blue and the membrane as the dashed red line. The gap sizes defined here are lower limits. (a) The 180 degree mountain folds require minimal gap between panels because the membrane folds back on itself. (b) The 180 degree valley folds require a minimum of twice the thickness of the panels because the membrane folds around two panels. (c) The 60 degree valley folds require a minimum of one thickness because of the triangle formed by the panel edges.

For the membrane model, the minimum spacing on valley folds undergoing 180 degrees of rotation is twice the thickness of the panels (Figure 3.8), as the membrane is applied to one side of the model only. The secondary valley folds undergo 60 degrees of rotation, and therefore could have a minimum spacing of one times the thickness (see Figure 3.8c). A wide range of materials can serve as candidate membrane materials. Fabrics, fiber-based tapes, and Kapton film were used in this work.

The flasher model can be adjusted for materials of different thicknesses. Figure 3.9 shows the prototype in 2.5 mm thick balsa wood. The rigid panels were taped on the side of the fold-line corresponding to the direction of the fold (mountain or valley). A gap was given in the valley folds (shown in Figure 3.9b) to enable the model to fold without requiring the panels to flex. Figures 3.9a and 3.9c show that the thickness of the one side of the stowed structure is equal to the combined thickness of the panels following the path outlined in orange; i.e., the number of panels along the orange path governs the thickness of the stowed structure.

The mathematical model and principles described for creating physical models can be used to design devices with a high ratio of deployed-to-stowed radius. The following section serves as a demonstrative example of implementation in a specific application.
3.4 Application

Although the principles and approaches presented in this paper are general and apply to a range of possible applications, a motivating driver for this work was the development of a compact deployable solar array for space applications. This application is described here to serve as an example of implementation of the fundamental research results.

Under NASA Technology Roadmaps, Flexible Material Systems refers to the “identification of flexible systems that enable the assembly of expandable structures from a small volume to a larger volume through the combined use of rigid linkages and joints with soft thin shells or membranes” [59]. A NASA Research Announcement [41] called for a mass and volume efficient solar array system. A large compression ratio of deployed-to-stowed diameter is needed to achieve the power requirement of 250 kW or greater. Origami folding patterns were used to inspire the folding of the solar array to achieve synchronous deployment.

For the solar array application, it is especially imperative that the rigid panels do not flex to prevent damage to the solar cells. Depending on the objectives of the design, the rigid panel can either be triangular or quadrilateral. For our purposes, we wanted to maximize the surface area to which the panels were affixed; therefore, quadrilateral panels were chosen. Thus, we proceeded with Option (2) to enable rigid-foldability of the model.
The design constraints for the deployable solar array are:

1. Initial power levels of 30-50 kW, with extensibility to 250 kW for future applications;
2. Stowed dimensions to fit in launch vehicle;
3. Synchronous deployment preferable.

For comparison, the International Space Station has 8 solar arrays, generating 84 kW of energy [60].

The models described here show promise as a large solar array deployer. They can be stowed around the circumference of a hexagonal spacecraft and deployed with a perimeter truss, illustrated in Figure 3.10. In the final model for the solar array, a membrane backing was selected to join the panels together. This was used together with the model designed to account for thickness. It necessitated the addition of gaps between the panels to enable rigid foldability. The model also required folding to occur in the membrane joints themselves, to preclude the solar panels from flexing. Therefore, the valley folds were given a gap width of 10 to 14 times the thickness of the panels. Mountain folds were given minimal separation to maximize the surface area of the panel.

The crease pattern was distorted using the algorithm described previously. In addition to the design constraints listed above, the following shape constraints were applied:
1. Hexagonal cross section \((m = 6)\)
2. Maximum height of folded form = 4.0 m
3. Crease pattern incircle = 25.5 m
4. Maximum diameter (circumcircle) of folded form = 4.25 m
5. Maximum width of any panel = 2.0 m
6. Maximum spacing of any two vertices = \((1 \text{ cm})\sec(30^\circ)\)

The six-sided flasher was accommodated for thickness via the mathematical model with \(m = 6, h = 4, r = 2,\) and \(\delta = 0.01,\) and by incorporating discrete spacing between panels, as per Option (2). A 1/20th scale model is shown in Figure 3.11. It was built using 0.5 mm (0.020 in) Garolite and 0.025 mm (0.001 in) Kapton film for the backing. The outer diameter is 1.25 meters. Gap spacing was included in the prototype to enable rigid foldability. Mountain folds require no gap. Valley folds are given more than the minimum 2x spacing to enable the panels to rotate away from each other during stow/deployment. The 1/20th scale prototype has gaps that are 14 times the panel thickness at the 180 degree valley folds, and 10 times the panel thickness at 60 degree valley folds. Optimization based on the kinematics of folding may enable the gap spacing to be further reduced. The gap spacing may also be constrained by panel width and height, i.e., a larger panel may necessitate a wider gap to allow sufficient shear in the membrane.

The model has a deployed-to-stowed diametral ratio of 9.2 (or 1.25 m deployed diameter to 0.136 m stowed diameter). This ratio will increase as rows of panels are added to the circumference of the model.

### 3.5 Discussion

The six-sided flasher has great promise as a large deployable array. It also represents a rich area for future research regarding the joints and general assembly of the rigid flasher. By introducing the additional hinges along the diagonals (making all panels into triangles), the flasher model is rigid foldable. However, the additional folds increase the total degrees of
freedom of the array. The ideal model would have exactly enough folds to result in a single-DOF mechanism. Loss of surface area coincident with this option makes it unfavorable for the solar array application. For this and other applications where that panel subdivision is undesirable, the alternative is to increase gap spacing between the panels. The flexing that would occur along the diagonal is now concentrated in the membrane at the gaps. The wider gap enables the use of quadrilateral panels (thus maximizing surface area for the application of solar cells).

With both models, an external structure is currently required to keep the deployed structure in a planar configuration. Possible future solutions include an integrated “skeletal” truss to support the panels internally, or a perimeter truss to hold the array in tension in its deployed configuration.

Actuation is another important area of research. One possible solution is to embed the actuation in the model itself, potentially through stored strain energy in deflected members or shape memory alloys (SMAs). The deployment can be guided from the outer circumference of the model with a perimeter truss. Stowing the model is slightly more challenging; the folds could be constrained to only fold in one direction (mountain or valley) from the planar state. At least six actuation points are currently needed to prevent the panels from binding on each other during the transition to the stowed state.
The membrane backing for the model can also be researched further. Preliminary testing was conducted with fabric as the membrane backing because the weave in the fabric allows shear at the membrane gaps and enables rigid foldability with smaller gap sizes. Mathematical models to quantify this motion have yet to be developed.

3.6 Conclusion

This work has proposed, developed, and demonstrated an approach for creating origami-based deployable arrays with non-zero thickness materials, and that have a high ratio of deployed-to-stowed diameter. A thickness-accommodating mathematical model has been described for the origami flasher. Practical modifications for hardware development were also proposed. The methods have been demonstrated in physical models and in a demonstrative application. By employing the approach presented here, similar modifications can be made to other zero-thickness models to enable their implementation in engineering applications.
CHAPTER 4. SOLAR SAILS

The work on the origami pattern for the solar array was also applied to the folding of solar sails for two NASA CubeSat missions, NEA-Scout and Lunar Flashlight. I collaborated with the Structural Dynamics Branch at NASA Langley Research Center (LaRC) to develop and demonstrate several folding patterns for an 80-100 m$^2$ solar sail, folded from 2.5 µm Mylar to fit inside a 2U CubeSat (10 cm x 10 cm x 20 cm). The folding patterns were derived from the same mathematical models created by Robert Lang, which I used in previous work [29].

4.1 Background

Solar sails use the solar radiation pressure to accelerate a spacecraft through space. This pressure is only 8.21e-6 Pa, which means solar sails are only a viable technology for space travel when the craft is very light and the sails are large [61]. Technology demonstration missions, including IKAROS and LightSail, have proven the deployability of solar sails [62, 63]. Additional missions are planned that use solar sails as the propulsion system, including Lightsail-D, NEA-Scout, and Lunar Flashlight [64–67].

4.2 Methodology

The folding patterns can be grouped into two categories: (1) folding the individual quadrants without accounting for thickness, and (2) folding the full sail as a single entity, while accommodating for thickness.

4.2.1 Folding Individual Quadrants

When folding the individual quadrants, I determined that the material was thin enough with few enough concentric folds (or folds that wrap around each other) that I could ignore the membrane thickness to simplify the folding pattern. In this case, the pattern is essentially
one segment from the origami flasher pattern, illustrated in Figure 4.1. The mountain folds are indicated with a solid line and the valley folds with a dashed line.

For the full size sail, each quadrant would need on the order of 128 creases to keep within the allotted volume in the CubeSat. A scaled version of one quadrant is shown in Figure 4.2. This prototype was folded from 2.5 \( \mu \)m Mylar, with edge reinforcement of 40 \( \mu \)m (1.6 mil) Kapton tape. The base of the triangle is 1.5 m (59 in), which makes this quadrant about 1/5th to 1/6th the size of the sail needed for NEA Scout or Lunar Flashlight.

There are a couple of benefits to using this folding pattern. First, the creases are roughly perpendicular to the tensile boom load, so that loading will tend to pull them flat. By neglecting thickness, the folding pattern is very simple; in fact, no pattern needs to be
transferred to the membrane. Each crease can be made by repeatedly folding segments in half.

4.2.2 Folding the Full Sail

The second option is to fold the entire sail from one continuous sheet of material. There are obvious benefits and challenges to this approach. On the one side, this approach will make it easier to keep the sail in one plane, especially if we diverge from the traditional square design and use a triangular sail. There is also the possibility of simplifying deployment if the sail is wrapped around a spindle and deployed from the center. On the other side, the folding is much more complex.

Because there are many concentric folds, thickness should be considered. Even though the membrane is vanishingly thin, when it is folded, you will have a stack of 200 layers that all need to crease about the same axis of rotation. Accommodating for thickness will also help account for folding errors, edge-reinforcement thickness, and added depth from the shear-compliant border. Accommodating thickness will result in a mathematically generated pattern that would need to be transferred onto the sail membrane. I do not know at this time how that would be done.

The modified origami flasher pattern can be generated for any polygon with three or more sides. The benefit of the triangle is that you can keep the surface in one plane. This is especially important for the Lunar Flashlight, since it has a reflectivity requirement. Figure 4.3 shows the square and triangular patterns for 1/10th scale of the full sail, accommodating thickness. The red lines indicate mountain folds, while the blue lines indicate valley folds. The grey lines enable rigid foldability, but for solar sails, this should not be an issue. We can just let the panels warp during the stowing and deploying (folding/unfolding) phases. This is likely to generate more “micro crinkles” in the membrane however.

Figure 4.4 shows the triangular prototype folded from CP1 polyamide in its partially deployed and stowed states. This prototype is not folded to any particular scale; it is only intended to demonstrate the performance of the membrane when folded in this manner.

With Jay Warren and Mark Griffith, we built a test setup to qualitatively demonstrate the effect of tensioning in the membrane on the creases and wrinkles in the quadrant. At
Figure 4.3: The folding pattern for the 1/10th scale prototype of the solar sail, accommodating for thickness. We’ve assumed a thickness of 25 µm to give a comfortable allowance for folding errors.

Figure 4.4: Triangular sail folded from CP1 polyamide.
Figure 4.5: As the equivalent boom load increases from 0.05 N (almost negligible) to 2.0 N, the fold creases are flattened. With increasing load, we also see the emergence of wrinkling along the edges, as expected.

the time of testing, the booms were expected to apply up to 1 N of load, equivalent to a nominal stress \cite{68} in the membrane of 750 kPa (110 psi). Figure 4.5 shows the effect of increasing boom load on an individual quadrant of the solar sail, folded from 2.5 µm Mylar, at about 1/10th scale. There is little discernible difference between 1.0 N and 2.0 N of boom load regarding how well the fold creases are flattened. With increasing load, we also see the emergence of wrinkles along the edge, as expected.

4.3 Observations

Accounting for thickness increases the folding complexity substantially. If we are safely able to neglect thickness, then the difficulty level is comparable to other methods used, such as
the z-fold on IKAROS [62]. This folding pattern for solar sails is advantageous because the deploying booms apply a tension that is largely perpendicular to the creases in the sail, which results in a flatter sail membrane.
CHAPTER 5. CUBESAT SOLAR ARRAY

5.1 Introduction

The CubeSat program is a promising avenue to put the solar array or solar sails into space for testing and proving their functionality [69–71]. The deployable array concept is easily scalable, although application to CubeSats does change some of the constraints on the design. The thickness-to-diameter ratio is larger, making the issues of thickness more pronounced. Because volume is very constrained on CubeSats, methods of actuation are also limited.

5.2 Background

Micro-satellites are 10-100 kg, cost roughly $10M, and take 2-3 years to develop. Nano-satellites are 1-10 kg, cost roughly $1M, and can be built in about a year. Pico-satellites are 0.01-1 kg. Under this definition, CubeSats are nano-satellites.

An example of a 1U (10 cm x 10 cm x 10 cm) CubeSat from CalPoly is shown in Figure 5.1. The antenna on this CubeSat wraps around a form that can extend up to 6.5 mm from the 10 cm cube. The portions of the cube within the rails (the black panels covered with solar cells in Figure 5.1) have an extra 6.5 mm of clearance on each side, in addition to the 10 cm dimension.

There are several areas where compliant mechanisms might be used in CubeSats, including hinges, deployables, and bistable switches. CubeSats are limited on size, power and mass, so deployable solar panels to increase power generation are one area of interest to CubeSat designers. Also, gravity-gradient booms help to stabilize the CubeSat while in orbit [72,73] and may be deployed with a compliant mechanism. Another area of application involves attaching a parachute to help the CubeSat de-orbit after its mission is completed [74–76]. De-orbiting is largely a function of surface area to mass ratio. Providing a means for
planned de-orbiting of the satellite helps comply with lifetime assessments. The satellites
cannot land on earth; they have to burn up in the atmosphere, which might constrain what
materials are used in the design of the CubeSat.

5.3 Design

The general design guidelines for CubeSats can be found at www.cubesat.org, which in-
cludes all CubeSat design specifications. Because of the CubeSat form factor, we created a
four-sided version of the flasher-based solar array (shown in Figure 5.2), which enables the
segments to be larger, while maintaining a comparable deployed surface area to a hexagonal
version. Further, this square design style uses the space available in a more logical manner.

With the large 25-meter array, the ratio of thickness to segmental area is small,
meaning that in relation to the size of each individual segment in the pattern, the panels
are relatively thin. But on the CubeSat size scale, the thickness is larger in relation to
the segmental area. Because of this, the piecewise curvature is more pronounced in the
modified origami pattern to accommodate the thickness of the panels, which can be seen
in Figure 5.2. We project the four-sided array to be capable of 60 W of power generation,
which is comparable to some of the best designs for CubeSat arrays that currently exist.
This assumes a 75% packing factor (75% of the surface area of the array is covered with solar cells), 30% cell efficiency, and 300 W/m² effective flux.

For the design shown in Figure 5.2, the following specify the dimensions of the array:

- Maximum diameter of payload (capable of being stowed in the open area of the folded array) = 5.23 cm
- Height of folded form = 10 cm
- Maximum diameter of folded form = 9.40 cm
- Deployed crease pattern incircle diameter = 51 cm

The solar cells would be affixed to a flexible substrate, such as Kapton or the photovoltaic blankets used in ATK’s UltraFlex array [38]. The prototype shown in Figure 5.3 is a full-scale model of the CubeSat array, with 0.5 mm Garolite panels to represent the solar cells and a 0.05 mm Kapton backing.
5.4 Thickness Accommodation in CubeSats

The thickness of the solar panels in the CubeSat model are expected to be approximately 2 mm thick, based on current solar panel options available for CubeSats. I used 2.4 mm (3/32") acrylic to represent the thickness expected for the CubeSat deployable solar array. With the thicker material, the panels interfere with each other, especially at the start of the second ring in the pattern, and inhibit the array to fold completely. Figure 5.4 shows the acrylic quad-flasher on a Kapton film membrane. I expected this pattern to only need the minimum spacing required (as defined in Chapter 3), but the spacing proved to be inadequate. The starting point for the second ring is a particularly challenging spot, when we switch from two panels in the gap to four. Possible solutions are to increase the gap or taper the edges of the panels. I also found that “stress relief” holes in the Kapton film, as shown in Figure 5.5, become increasingly necessary with the thicker panels.

The spacing is inadequate for the model shown in Figure 5.4 because of the way the mathematical model defines the spacing between consecutive vertices in the folded form. The issue is illustrated in Figure 5.6. If we take one section of the array, identified in Figure 5.6a and 5.6b, then the folded form of that section would look like the to-scale cut-away shown in Figure 5.6c. If the membrane material at the crease isn’t deformed or flattened when folded,
Figure 5.4: The 2.4 mm (3/32”) acrylic panels interfere with each other, especially at the start of the second ring.

Figure 5.5: (a) The folded form of the quad-flasher, showing the excess membrane in the valley folds. (b) The unfolded quad-flasher, with $4t$ gaps at 90° valley folds, $8t$ gaps at 180° valley folds, and with stress-relief holes.
then the rigid panels will run into each other at the corners, as shown in Figure 5.6c. This means the panels interfere with each other well before they reach the minimum $2t$ spacing for valley folds. Again, this assumes that the creases are at single points, rather than the membrane being evenly distributed across the space between panels. This may be the case, since the positions of all facets are dictated by their connection to other facets in the model.

Figure 5.5 shows a version of the four-sided flasher where the spacing between panels at valley folds is increased to accommodate for thickness. At 90° valley folds, the gap is 10 mm (approximately 4t) and at 180° valley folds, the gap is 20 mm (about 8t). The model is easily able to fold, indicating that these gap sizes are excessive, and could be reduced. The optimal gap spacing has yet to be defined.

5.5 Deployment

The Cal Poly Picosatellite Orbital Deployer (P-POD) is shown in Figure 5.7 [77, 78]. The P-POD is used to store the CubeSats on the launch vehicle during launch, and then jettison them into space. The deployer has a large coil spring that is compressed when the CubeSats are in place. Two torsion springs control the opening of the door. A burn-wire release
mechanism holds the door closed until actuated. Rails in all four corners of the P-POD guide the CubeSats as they exit the deployer. Separation springs (plunger springs) are used between CubeSats to maintain a specified distance between them.

The deployment methods for the solar array are discussed in [45]. The most promising methods at this stage of development are using shape memory alloys (SMAs) or relying on centripetal acceleration. The necessary temperature change for actuation is created by running a current through the SMA. The array would be launched in its stowed state and, after being ejected from the P-POD, a current would be applied to the SMAs to cause them to transition to their second position, thereby opening the array.

Alternatively, if there isn’t any stiffness in the joints of the array, spinning it will deploy the panels as well. The biggest concern is deployment reliability, or whether the panels will unfurl completely. An additional design component may be required, which would lock the panels into a flat sheet once deployed.

5.6 Discussion

CubeSats are the most likely avenue to launch a solar array using this origami-inspired design because CubeSat missions are relatively inexpensive. It is possible to launch the solar array as a technology demonstration mission, but it would also be desirable to team up with a group that has science they want to perform, so that we’re getting more out of the mission.
Some of the testing that may be required prior to inclusion in a CubeSat includes random vibration, sine sweeping, thermal bakeout, thermal cycling, shock, and electrical and battery testing. Another option to consider would be to use the solar array in a satellite swarm to increase the power generation.

This design for the solar array occupies one unit (1U) of the CubeSat. This may be a less desirable design feature because instrumentation cannot be stowed as easily as in CubeSat designs with solar panels that only fold once down the side of the cube [37]. The TurkeyTail, for example, is six panels that fold over on themselves, but they sit on the outside of the CubeSat, so the rest of the volume is available for the satellite instrumentation.

A possible benefit of the flasher design is that the panels may be more protected during launch because they aren’t on the external faces of the CubeSat. Further, the folded form of the array leaves a hollow area in the center of the array in which some instrumentation or other payload could be stored. Therefore, the 1U in which the array is stored is not entirely occupied by the array.

5.7 Funding Opportunities

NSF will sponsor university CubeSat missions for about $1M. The Air Force also sponsors a University NanoSat Program. NASA Ames/OCT sponsors the Edison Small Satellite Demo Missions (with a focus especially on technology, rather than science). NASA’s ELaNa (Educational Launch of Nanosatellites) program will sponsor the full cost of the launch of the satellite, if your application is accepted. Other launch opportunities may be possible through commercial providers, including SpaceX ($390K for a launch), Orbital, or Atlas V.
CHAPTER 6. DEPLOYMENT METHODS FOR AN ORIGAMI-INSPIRED RIGID-FOLDABLE ARRAY

6.1 Introduction

The purpose of this work is to evaluate several deployment methods for an origami-inspired solar array at two size scales: 25-meter array and CubeSat array. The array enables rigid panel deployment and introduces new concepts for actuating CubeSat deployables.

The design for the array was inspired by the origami flasher model [18,19]. Figure 6.1 shows the array prototyped from Garolite and Kapton film at the CubeSat scale. Prior work demonstrated that rigid panels like solar cells could successfully be folded into the final stowed configuration without requiring the panels to flex [29]. The design of the array is novel and enables efficient use of the volume available in the launch vehicle. The array can be wrapped around the central bus of the spacecraft in the case of the large array, or can accommodate storage of a small instrument payload in the case of the CubeSat array. The radial symmetry of this array around the spacecraft is ideally suited for spacecraft that need to spin.

This work focuses on several actuation methods for a one-time deployment of the array. The array is launched in its stowed configuration and it will be deployed when it is in space. Concepts for both passive and active actuation were considered.

6.2 Actuation Concepts

Several methods of actuation have been explored, including a motor-driven perimeter truss, pneumatic actuation, centripetal acceleration, stored strain energy, and thermal activation (with a shape memory plastic). Because of the size of the panels in the 25-meter array, the

\footnote{Portions of this chapter were presented at the 2014 Aerospace Mechanisms Symposium, and a paper of the same title was included in the proceedings of that symposium.}
perimeter truss is desirable to support the deployment motion. For the CubeSat array, a less bulky actuation method is preferable. Pneumatic actuation, centripetal acceleration, stored strain energy, and thermal activation of a shape memory plastic were demonstrated at that scale.

6.2.1 Motor-driven Perimeter Truss

A scale model of an array and truss, shown in Figure 6.2, were prototyped to demonstrate the functionality and interaction of the two. The truss was SLA-printed, the connecting flexures were 3D-printed in Nylon, and the array was prototyped from Garolite and Kapton. Astromesh, which has a motor-driven actuation, is flight-proven and would likely be used in the final design, should the array be selected for a flight project. Since our objective is primarily to show the interface between the array and the truss, we have sought to imitate the motion of the AstroMesh deployment without motorizing the model.

Torsion springs, shown in Figure 6.3, were attached to the truss to bias the truss open; i.e., the springs are deflected when the array and truss are stowed. This method of stored strain energy makes the array self-deploy; however, we’ve guided the deployment to mimic motorization of the truss. The goal was to demonstrate a fixed rate of extension for each of the six sectors of the array. There is some clearance in the joints that prevent the truss from...
being a single-degree-of-freedom system, and therefore must be actuated at several points to deploy synchronously. When the center of the array is fixed, the truss rotates around the fixed center about one-and-a-half times to deploy the array.

I have created a virtual work model of the energy stored in the perimeter truss when the torsional springs are deflected. The virtual work model is illustrated in Figure 6.4. For two mirrored bays, the vertical restoring force is:

\[ F_{out} = -\frac{2(k_1 + k_2) \theta}{l \cos \theta} \]  

(6.1)
where \( k_1 \) and \( k_2 \) are the spring constants for the torsional springs, \( \theta \) is angle of deflection, as illustrated in Figure 6.4, and \( l \) is the length of the longerons. The springs are assumed to be undeflected when the bays are fully extended (i.e., the angle between the batten and longerons is 90 degrees, or \( \theta = 0 \)). As the bays deploy, they apply a force against adjacent bays, pushing the entire structure apart and open. For the basic case illustrated in Figure 6.4, the force \( F_x \) applied against adjacent bays is:

\[
F_x = \frac{(k_1 + k_2) \theta}{l \sin \theta}
\]

(6.2)

In the circular truss, only a component of this force is applied against adjacent bays, as each bay is set at an angle to the next.

We considered two different attachment points on the array: directly on the panels or at the membrane between panels. To avoid ripping the Kapton film, we opted to attach directly to the panels. The challenge with attaching to the panels is that they undergo a complex rotation from the deployed to stowed position. The joint needs to undergo a 90° torsion as well as bend 90° to one side. We chose a serpentine flexure, shown in Figure 6.5, to accomplish this rotation.

The primary drawback of this joint is that it doesn’t constrain any degrees of freedom. However, it does allow the complex rotation and allows for some extension of the joint as the distance between the array and the truss isn’t necessarily constant, especially considering
the rotation of the panels. Having a compliant joint that can accommodate that change in distance as well as complete the two-axis rotations is beneficial. It enables the two structures to interface.

The flexures are secured to the truss with screws. We opted to glue the flexures to the panels, although they could also be pinned or bolted to the panels. There is some slight interference with the ends of the flexures and the final folded form of the array (i.e., the outermost panels cannot sandwich perfectly flat against each other).

We tested a cable-driven actuation method on a portion of the bays from the perimeter truss, shown in Figure 6.6. The cable-driven prototype has a good mechanical advantage when the input cable is perpendicular to the truss members, but the low transmission angle that occurs when the bays are fully stowed results in binding if the actuation cable is pulled straight down.

6.2.2 Pneumatic Actuation

For pneumatic actuation, a plastic bladder was adhered to the back of the array and inflated with compressed air. If the bladder were designed to be air tight, it would remain inflated after the array opened and provide a semi-stiff support for the array. A simple mock-up of an
array with an inflatable bladder was created to demonstrate that the concept of pneumatic actuation is very plausible for the array.

6.2.3 Centripetal Acceleration

Centripetal acceleration was also considered as a means for deployment. This method requires no additional actuation hardware integrated with the array. This deployment method can be accomplished by spinning the satellite. A torsion-spring deployer was fabricated with initial results recorded under high-speed video.

The torsion-spring deployer, shown in Figure 6.7, consists of a 3-D printed test base with a torsion spring mounted in the base. The torsion spring selected was a steel music wire spring with 19 mm (0.748”) OD and 2.2 mm (0.085”) wire diameter, providing 1.45 N-m (12.86 in-lbs) of torque. The array fits snugly over the small hexagon which holds the array in place as the spring is displaced. We have demonstrated a rapid deployment of the small arrays with the centripetal acceleration from the torsion spring as it is released.
6.2.4 Stored Strain Energy

Strain energy can be stored in the array in a variety of ways. One approach evaluated at the CubeSat scale is to affix tape springs radially along each sector, shown in Figure 6.8. The prototype array opened quickly, but did not lay perfectly flat; therefore, a mechanism to lock the panels in their deployed configuration may be desirable. We also prototyped a circumferential pattern, shown in Figure 6.9. The radial springs allow for smoother and more reliable deployment, while the circumferential springs provide a beneficial structural stiffening in the final deployed state.

6.2.5 Thermal Activation

Shape memory polymers (SMPs) are specialized plastics with a low transition temperature (relative to its melting temperature), at which the plastic becomes malleable and can be molded into a new shape. When cooled, the plastic retains that new shape until heated again past its transition temperature. We experimented with 0.79 mm (1/32”) thick sheets of shape memory plastic as a means of actuating a deployable solar array, as can be seen in Figure 6.10. The SMP was folded without affixing any rigid panels, but as can be seen in Figure 6.10a, the facets are all curved. Also, the folds all have a rounded radius; i.e., they are not perfect creases.
The plastic has a transition temperature of 105°F and a melting temperature of around 400°F. I traced a segment of the quad-flasher on the plastic and ran hot water over the plastic to make it malleable for folding. The plastic must be fully cooled below its transition temperature to rigidly hold the new shape; otherwise, the folds will loosen slightly. Figure 6.10a shows the plastic when folded into the quad-flasher.

The shape memory plastic can be folded into the pattern for the array and then thermally activated to return to the flat (or deployed) configuration. Alternatively, strips
of the plastic can be affixed to the rows of panels that wrap around the central bus, rather than having the shape memory plastic cover the entire back surface of the solar array. This reduces the material thickness that must be added to the array, but may complicate the thermal activation if the strips are fully isolated from one another. As the added volume of the SMP to the array is very slight, this method of actuation has potential application to deployable arrays on CubeSats or other small satellites, where volume is especially critical.

6.3 Lessons Learned

Once deployed, certain methods of passive actuation (such as centripetal acceleration and stored strain energy) may require an additional mechanism to lock the panels into their deployed state to keep the array flat. As uncontrolled methods of deployment are undesirable, such a latching mechanism is necessary to reduce the chance for failure with these methods of actuation.

For communications applications, the requirements for the final shape are more stringent than for some other applications. At this stage, the flatness of the final deployed configuration has not been evaluated, but the latching mechanism described above could provide a solution to keep the panels at a consistent flatness.
During testing, we observed that some of the actuation methods caused strong vibration loads on the panels. This was especially the case for the centripetal acceleration method and stored strain energy method, but was also observed to a lesser degree in the pneumatically actuated model. Further analysis and selection of final materials are needed to determine how detrimental these vibration loads will be to the structure and wiring.

If thermal activation of a shape memory polymer can be achieved for in-space deployment, this method will be most promising for the CubeSat array. The actuation is slow enough to not induce vibration loads in the panels, and the material has a thin profile which takes up little of the constrained volume.
7.1 Introduction

The demand for clean energy is growing, and even constitutes one of the Grand Challenges identified by the National Academy of Engineering [79]. As fossil fuels continue to deplete, a new source of energy is needed to meet the growing energy demands. Solar energy is a reliable source of clean energy and can be used both on Earth and in space. Solar cells arranged in an array that can be compactly folded and stowed can extend the benefits of solar energy to new or undeveloped areas of application, including small satellites, and backpacking or military applications.

The objective of this work is to develop a map-fold-based, self-deployable array suitable for a solar array. Using techniques of origami, the intent is to create a solar array that is capable of folding into a fully dense form. To be fully dense when folded, the panels must have no gaps between them. The design was inspired by a patent of a tapered map fold by Charles Hoberman [3], which can be modified into a self-deploying array by adhering the panels to an elastic membrane on one side. Because of the panel thickness, the membrane necessitates further modification of the pattern: namely, spacing between panels at valley folds. These modifications enable the model to fold up into a fully dense volume when stowed. The stored strain energy in the folded elastic membrane enables the array to self-deploy.

The mechanism must be capable of reaching a fully dense state for portability. If the array is not fully dense, external loads (such as might inadvertently occur in a backpack or during shipping) would apply moments on the outermost panels and likely damage the solar energy.

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1 The content of this chapter was included in the proceedings of the 2013 ASME Conference on Smart Materials, Adaptive Structures and Intelligent systems. The conference paper was co-authored by Mary Wilson, Spencer Magleby, and Larry Howell.
cells or the hinges between panels. Crystalline silicon solar cells have the most established cell technology, so it is assumed they will be used as the solar cells in the array. Because the cells themselves are brittle, an array of these cells can be folded only if the membrane to which they are attached can be folded without requiring that the panels (or solar cells) flex.

7.2 Background

Origami-inspired folding of deployable systems increases the portability of the array and enables greater energy production because a larger array can be stowed in a smaller package. Because origami crease patterns are designed for zero-thickness material, the pattern must be modified to accommodate for thickness of real materials. “Rigid-foldable origami” defines those models that can still be folded when the facets are replaced with rigid panels and the creases are replaced with hinges [9, 10].

One approach to solving the problem of rigid-foldability is to add hinge components to the model to enable the folding of thick, rigid materials. Hoberman [3, 12, 13] has presented several approaches related to this concept. In some models [3], tapered strips accounted for material thickness and ordered pleating enabled the thick sheets to collapse on themselves. In other models, the hinges are constrained to lie in different planes so their axes do not intersect [13]. These offsets enable the mechanism to be rigid-foldable into a compact unit. Hoberman mechanisms were used by Faist and Wiens in 2010 in the design of deployable antennae and solar arrays [14].

The Miura-ori model, shown in Figure 7.1a, is one of the landmark rigid-foldable deployable structures [1, 2, 80]. The Miura-ori fold pattern is similar to the map fold, but with non-right angles between facets to enable synchronous deployment of the entire sheet with only one degree of actuation. When $\phi = 90^\circ$, the crease pattern is that of the map fold, shown in Figure 7.1b, which must be unfolded entirely in one direction before the perpendicular direction can unfold. The mathematics and science of map-folding have been researched for over forty years [81–83], although little has been published on developing a rigid-foldable model of the map fold with thick materials.
A novel design for a passively deployed solar array was presented by Campbell et al. in 2006 [84]. Strain energy is stored in rolled longerons and other frame elements. The energy is released when the frame is heated passively by the sun.

Malone et al. presented a concept for a lightweight inflatable solar array [85]. The array of solar cells is adhered to a thin Kapton film and is accordion-folded to a compact volume. Two parallel booms running along the sides of the array are inflated simultaneously with dry nitrogen to deploy, or unfold, the array.

Techniques for rigid-foldability similar to those presented in this paper were also applied to an origami model from the “winding membrane” family [16] to develop a large deployable solar array for spacecraft [86].

7.3 Rigid-foldable Design

Two concepts were pursued for the compactly stowable array: the map fold (Figure 7.2a) and the tapered map fold from Hoberman’s patent [3] (Figure 7.2b). To develop a rigid-foldable model of the map fold, spacer panels were added to the model, as shown in Figure 7.3. A “spacer panel” is a new piece of material that is inserted in the gap made at the hinge line. A benefit of this approach is that the hinge material can now be used as part of the surface (e.g., in the application discussed in this paper, solar panels can be attached to the spacer
panels as well as to the original panels). Therefore, the space isn’t lost to the hinges, but can be used to an advantage.

The tapered map fold design has a similar component, that we will refer to as “tapered spacer panels”, to enable rigid-foldability. Prototypes of these two rigid-foldable models were made from 0.05” mat board, and are shown in Figure 7.4.

The map fold in Figure 7.3 is comprised of square-shaped panels and rectangular-shaped spacer panels that act as hinges to accommodate for the panel thickness. The map fold is capable of reaching a fully dense form; however, the panels separate during the folding motion, as shown in Figure 7.5. This prevents the panels from aligning when folding and, therefore, doesn’t allow the panels to be attached directly to each other. While this undesirable effect can be reduced through the use of thinner panels and a membrane on one side, it cannot be eliminated completely, as shown in Figure 7.6.

A further challenge of the rigid-foldable map fold is a translational sliding motion that occurs between strips of panels. A general solution for panels of any thickness may be a sliding revolute joint between the rows to enable both the translational motion and rotational motion that occur as the model is folded. If the panels are thin enough, it is possible to use an elastic membrane to connect the panels, which allows enough stretch (or shear) in the
Figure 7.3: A 5x5 map fold pattern designed for a material with thickness, $t$. Spacer panels are shown in darker gray. The columns of panels will translate (or shear) relative to each other. This layout minimizes that shear.
Figure 7.4: (a) The map fold uses spacer panels to enable rigid-foldability. The panels are joined at the valley folds by an adhesive membrane. All of the panels are adhered to an elastic membrane (not shown) that holds the panels together. (b) The model of the tapered map fold was assembled using rows of tapered spacer panels and an adhesive membrane at each of the valley folds.

Figure 7.5: A 3x3 map fold array made from 0.25-inch thick foam-core panels. As it folds, the panels separate from each other, resulting in a gap as shown in (b).

Figure 7.6: A 5x5 map fold array made from 0.05-inch thick panels with an elastic membrane applied to one side. Even with a greatly reduced panel thickness, the panels (a) still visibly separate during the folding motion, before (b) achieving the fully dense configuration.
Figure 7.7: (a) A “pleat” fold, with mountain folds indicated by solid lines and valley folds indicated by dashed lines. (b) When folded, the facets shear relative to one another by a vertical offset, \( v \).

direction of translational motion. This was done for the model shown in Figure 7.4a and Figure 7.6. Another potential solution for the translational motion between rows of panels is a “pleat hinge”, shown in Figure 7.7, that accommodates the shear necessary between panels.

The tapered map fold (shown in Figure 7.4b and Figure 7.2b) resolves this issue. This model was assembled with alternating adhesive hinges (i.e., the tape is on alternating sides of the panels to correspond with the valley folds). Like the Miura-ori, this model is capable of full-sheet deployment with a single degree of actuation. This is because of the tapered spacer panels (Figure 7.4b). Further, unlike the traditional map fold, the panels do not separate as it folds. Rather, the adjacent panel faces continuously approach each other until they meet. The tapered map fold is shown in Figure 7.8, with taped valley folds. Figure 7.8c illustrates that an incorrect dimensional relationship will inhibit the model from reaching a fully dense configuration.

When comparing the map fold to this tapered configuration, the tapered map fold is preferable since it only requires one degree of actuation and does not exhibit the same issue of separation between panels as it folds. Although this is not the case in Figure 7.8, by choosing appropriate dimensions, the model is capable of reaching a fully dense form. The critical dimensions for achieving the fully dense form are defined in Figure 7.9.
Figure 7.8: Sequence of the tapered map fold as it folds: (a) Unfolded configuration showing alternating adhesive hinges (tape on alternating sides corresponding to valley folds). (b) Partially folded model. (c) Completely folded configuration that is incapable of reaching a fully dense form.

We chose to constrain the parallelograms to be rectangles, although this is not required for the model to be rigid-foldable. The length $d$ of the largest tapered panel is the equal to twice the sum of the thickness, $t$, of all panels in a vertical column. For the model in Figure 7.9, $d = 8t$. The second tapered trapezoid would then have a length of $6t$ at the top of the trapezoid, and so on. The angle $\alpha$ is driven by $t$ and $h$, and can be calculated as follows:

$$\alpha = 180^\circ + \arcsin\left(\frac{t}{h}\right).$$ (7.1)

The length, $l$, and height, $h$, of the panels are free choices for the designer. In the modified tapered pattern (Figure 7.9b), the panels are kept at the same height, $h$, but a gap, $g$, is added between panels to accommodate for the panel thickness, $t$, at valley folds.

7.4 Self-deployable Design

To simplify manufacturing and enable self-deploying, a membrane was applied to one side of the panels (see Figure 7.10). The membrane used in these prototypes is a “performance mesh” fabric of 99% polyester and 1% spandex. This required some modification of the original tapered map fold design, as shown in Figure 7.9b. A gap $g = 2t$ replaced valley folds to accommodate for thickness of the panels. These modifications enable the model to fold into a fully dense volume when stowed. Similar work was done with the origami flasher model to create a large deployable array [86].
Figure 7.9: Comparison of the tapered map fold pattern and the modified pattern. The rectangular panels are all \( l \) by \( h \) rectangles. The angle, \( \alpha \), is driven by \( t \) and \( h \). The width of the largest tapered spacer panel, \( d \), is equal to twice the sum of the thickness, \( t \), of all panels in a vertical column (in this case, \( d = 8t \)). The length, \( l \), and height, \( h \), of the panels are free choices for the designer. (a) The tapered map fold crease pattern is shown, with valley folds indicated by dashed lines. (b) In the modified tapered pattern, the panels are kept at the same height, \( h \), but a gap, \( g \), is added between panels to accommodate for the panel thickness, \( t \), at valley folds, with a membrane applied to one side of the panels.

A uniform gap, \( g \), was applied to all valley folds; however, the gap could be determined respective to each valley fold and the total rotation of that joint. As illustrated in Figure 7.10, for 180° folds, the full \( g = 2t \) is required, assuming negligible membrane thickness. For 90° valley folds, this can be reduced to \( g = \sqrt{2}t \). For a fully dense model, all fold angles will either be 180° or 90°.

Several prototypes were made to evaluate the effect of the modifications we made. The membrane-backed model, shown in Figure 7.11, does not achieve a fully dense folded configuration, but the panel faces rotate a full 90° until the panel faces are sandwiched against each other. The length, \( d \), of the tapered panels is half of the necessary length, which prevents this model from reaching a fully dense form. Once those dimensions were adjusted as described above, the modified pattern was able to fold up into a fully dense form, as shown in Figure 7.12. Figure 7.13 illustrates that the panel dimensions \( l \) and \( h \) are free design choices.
Figure 7.10: The membrane is applied to the back side of the panels, with a thickness of $t$. The minimum gap size, $g$, is dependent on the angle of the valley fold, as shown. Assuming negligible membrane thickness, for 180° valley folds, a minimum gap size of $g = 2t$ is required. For 90° valley folds, the minimum gap size reduces to $g = \sqrt{2}t$.

Figure 7.11: First prototype of modified tapered map fold (a) unfolded model which shows the necessary spacing between panels in order to incorporate a membrane to one side. (b) Modified tapered map fold folded completely.

Figure 7.12: Model of modified tapered map fold. (a) Unfolded. (b) Fully dense model of modified tapered map fold.
Figure 7.13: Model of modified tapered map fold, illustrating that the panel dimensions \( l \) and \( h \) are free design choices. (a) Unfolded. (b) Fully dense model of modified tapered map fold.

![Figure 7.13](image)

Figure 7.14: In this arrangement of the tapered map fold pattern, the panels are parallel with the horizontal, rather than extending perpendicular to the angled spacer panels. (a) The deployed configuration is flat. (b) The stowed configuration is not quite fully dense.

![Figure 7.14](image)

7.5 Discussion

There is still more research to be done on this modified tapered map fold array. Further research will include a more detailed understanding of the angles so that the optimal angle is chosen. The angle between the tapered spacer panels and the rectangular panels affects the model’s ability to reach a fully dense form. When there is no angle, the model is incapable of completely folding up (Figure 7.14); however, this may be remedied by adjusting the length, \( d \), of the tapered spacer panels.
membrane stretched across gap between adjacent panels

Figure 7.15: Model of modified tapered map fold shown at an angle to display that the membrane stretches across the gap between adjacent panels. This stretch in material is the source of strain energy the model uses to self-deploy.

The stored strain energy in the elastic membrane enables the modified tapered map fold to self-deploy. The deployed state is designed to be the lowest energy state of strain energy, so the model wants to go to that position, creating a self-deployable array. The greater the tension in the membrane, the faster the array deploys. The elastic membrane also provides some forgiveness in the dimensioning and fabrication of the array. As seen in Figure 7.15, the gap between adjacent panels is greater than the theoretical (at this right-angle fold, the inside edges of the two outermost panels should still be touching).

The application of a membrane to one side of the model decreases fabrication time. This allows the model to be both cut out and assembled flat before folding up into its stowed configuration. The modified tapered map fold was cut out on a laser cutter in one sheet and then the membrane was applied with a spray adhesive. Small tabs connected the panels and held them together until the membrane was applied.

7.6 Conclusion

Origami models are created assuming zero (or near zero) thickness. When a material with finite thickness is used, the panels are required to bend around an increasingly thick fold as crease lines are stacked. To create these models from materials with finite thickness,
adjustments must be made to the original origami crease patterns to accommodate material thickness.

The tapered map fold [3] (shown in Figure 7.2b) accounts for material thickness, while the map fold (shown in Figure 7.2a) required “spacer panels” to achieve rigid foldability. The key modification to the tapered map fold model is the application of an elastic membrane to one side of the panels, with adequate spacing between panels at valley folds, to create a self-deployable array. Similar results were achieved with the map fold. However, the map fold array requires actuation in two perpendicular directions to achieve its fully dense stowed configuration. In both the map fold and modified tapered map fold, panel thickness is accounted for and stored strain energy in the membrane causes both models to self-deploy.

Potential applications for the array include a collapsible solar array for space applications, or military and backpacking applications. Future work will include quantifying the energy storage and rate of deployment for different membranes and layouts, and creating a working solar array prototype with crystalline silicon solar cells.
Bistable mechanisms are proposed as a potential solution for latching or deploying the solar array. When the array is in its stowed configuration, a compliant bistable mechanism may be employed in place of a pyromechanical release device. Smaller bistable mechanisms may be embedded into the matrix of the substrate to functionally lock the array in its deployed configuration. Creating such mechanisms using compliant mechanism theory results in devices that are easily fabricated and do not create friction or require lubrication.

8.1 Introduction

Compliant mechanisms perform their function through the elastic deflection of their members. The advantages of compliant mechanisms include increased performance, reduced or eliminated assembly, no friction or wear, fewer parts, lower cost, and lower weight. These advantages make compliant mechanisms ideally suited for space or aerospace applications, where low weight and no lubrication are desirable [4].

Compliant bistable mechanisms [87, 88] gain their bistable behavior from the energy stored in the flexible segments, which deflect to allow mechanism motion. This approach integrates desired mechanism motion and energy storage to create bistable mechanisms with dramatically reduced part count compared to traditional mechanisms incorporating rigid links, joints, and springs. As a deflection is applied to the mechanism, it rapidly transitions from one stable position to the next. The force-deflection response for a typical bistable mechanism is illustrated in Figure 8.1. An optional preload stabilizes the mechanism for lower force inputs.

Compliant bistable mechanisms can be used in space applications as switches, latches, or relays, thereby eliminating friction and improving the reliability and precision of those
Figure 8.1: The force-deflection response for a typical bistable mechanism is shown. An optional preload stabilizes the mechanism for lower force inputs.

mechanical devices. Such mechanisms could be integrated into deployment systems as non-explosive release mechanisms.

8.2 Background

8.2.1 Compliant Space Mechanisms

Compliant mechanisms have many advantages for space or aerospace applications and significant performance gains are possible with the introduction of compliant mechanism technology [4]. Current space-related applications of compliant mechanisms are largely limited to flexures in precision instruments such as optics. Flexures were also used in the wheels of the Mars Science Laboratory and Mars Exploration Rovers to provide suspension. Flexures have also been used to compensate for different coefficients of thermal expansion in different materials [5]. A compliant hinge providing 90 degrees of rotation was recently developed as a potential hinge for deployable booms on spacecraft [6] and compliant elements have been proposed for use in deploying booms [89].

8.2.2 Bistable Mechanisms

Compliant mechanisms can achieve bistable motion without bearings or friction. They can be designed to provide precise state positions. Compliant bistable mechanisms, such as that shown in Figure 8.2, have potential application in space systems as switches, latches, or as
an alternative to pyromechanical release devices [21–24]. Bistable mechanisms are flexible devices with two stable equilibrium positions. A pseudo-rigid-body model (PRBM) [90] is shown for a generic translating compliant bistable mechanism in Figure 8.3. The PRBM is overlaid on the bistable mechanism in Figure 8.4. The compliance in the mechanism is modeled by the inclusion of torsional and linear springs where

\[ K_1 = K_3 \frac{2\gamma K_\Theta EI}{l_c} \]  \hspace{1cm} (8.1)  

\[ K_2 = \frac{3EI_b}{w_i^3} \]  \hspace{1cm} (8.2)  

with \( K_\Theta = 2.67617 \) and \( \gamma = 0.8517 \). Further, for the bistable mechanism labeled in Figure 8.2, \( I = bt^3/12 \) and \( I_b = bh_i^3/12 \), where \( b \) is the material thickness (into the page). The PRBM is useful for initial design to find bistable configurations; then finite element analysis (FEA) is valuable to verify and refine the design. The PRBM gives reasonably accurate deflections and rougher approximations for stress.
Compliant bistable mechanisms \([87,88,91]\) take advantage of stable minimum-energy points in their geometrically nonlinear elastic energy curves. These mechanisms are specifically engineered so the energy stored in the deflected mechanism can be quickly released when the device is actuated. This approach integrates desired mechanism motion and energy storage to create bistable mechanisms with dramatically reduced part count compared to traditional mechanisms incorporating rigid links, joints, and springs. As a deflection is applied to the mechanism, it rapidly transitions from one stable position to the next, as illustrated in Figure 8.1.

Bistable mechanisms have an established history, especially in micro devices [91–94]. Their application to macro devices, particularly in metals, and for space applications is still relatively novel. One exception is the Bearing Active Preload System (BAPS) [26,27]. In this bearing ring, bistable mechanisms are used to apply a high preload during launch and a low preload during flight. The bistable mechanisms are SMA-actuated, but must be manually reset in the current design. Bistable mechanisms together with dielectric elastomer actuators were proposed for robotics for planetary exploration [95,96]. They have also been proposed for use in architecture in the development of retractable structures [97].
often been used in CubeSats and proposed for other space applications to enable bistability of space structures [98–100].

It is desirable to develop bistable mechanisms in metals because metals are more robust in many situations than polymers. They can withstand harsh environments such as space imposes. Metals can withstand higher loads than polymers and are less susceptible to creep and stress relaxation. They are also thermally and electrically conductive, which can be desirable for certain applications, including actuation.

8.2.3 Materials Selection

An integral part of designing CMs for space applications is material selection. For compliant mechanisms, we often consider the strength-to-modulus ratio of a material as a measure of its fitness for compliant applications. For space mechanisms, weight becomes critical as well. Table 8.1 compares the ratio of material yield strength to elastic modulus and density ($S_y/E \rho$) for commonly used materials in the space industry. Amorphous metals rank highest, followed by aluminum alloys 7050 and 7075, and then titanium, Elgiloy, and Inconel 718 (see Table 8.1). Aluminum has the lowest density of all the materials considered. Tantalum is very dense, but it is a refractory metal, highly corrosion resistant, and heat resistant. Invar, like tantalum, has a low coefficient of thermal expansion, making it ideal for optics.

Bulk metallic glasses (amorphous metals) are a new area of materials research. They can have high fracture toughness, although they are also characterized by a low ductility [101–
Metallic glasses are strong due to their lack of defined grain structure, but also have an elasticity comparable to conventional metals. The absence of microstructural defects also improves their resistance to corrosion [103]. Metallic glasses, with their exceptional yield strain, are an excellent prospect for compliant space mechanisms.

### 8.3 Bistable Mechanism Design

Several iterations of the bistable mechanism design are illustrated in Figure 8.5. Figure 8.5a shows the basic form of the bistable device. Figure 8.5b and Figure 8.5c show the addition of thicker midsections to the flexible beams. Such midsections are common on early bistable devices, but were included primarily because of the limitations on analytical methods; the pseudo-rigid-body model for small-length flexural pivots was originally used to model these flexures [90]. Such segments may also improve the stability of the mechanism by directing the flexible segments through a more defined motion.

Finite element analysis was used to determine the effect on performance of these thicker midsections. A brief analysis of the effects is shown in Figure 8.6 and Table 8.2. The thicker segments increase the bistable actuation force slightly, which helps the mechanism hold its second stable position. However, the stress is also increased with the addition of these thicker segments; the longer the thick segment, the greater the force and stress increase.

#### 8.3.1 Project Description

The objective is to design a bistable compliant mechanism with properties suitable for potential application as a release mechanism in space systems. An amorphous metal, or bulk metallic glass (BMG), was selected because of its properties described earlier. As with other metals, metallic glasses are corrosion-resistant and able to withstand the harsh environment of space. It is also noteworthy that metallic glasses can be manufactured by a process similar to injection-molding for plastics [106]. This has the potential to reduce manufacturing and labor costs. The composition of the alloy selected for the design was 41.2% Zr, 13.8% Ti, 12.5% Cu, 10% Ni, and 22.5% Be (Vitreloy 1). The pertinent material properties are $S_y = 1.8$ GPa and $E = 95$ GPa. Metallic glasses have a high strength-to-modulus ratio,
Table 8.1: Strength-to-modulus and density ratios for commonly used materials in the space industry.

<table>
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<th>Property Ratios</th>
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<td>$E$ (GPa)</td>
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<td>95</td>
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<td>2.8</td>
</tr>
<tr>
<td>Teflon FEP film</td>
<td>0.012</td>
<td>0.48</td>
</tr>
<tr>
<td>Tefzel film</td>
<td>0.006</td>
<td>1.2</td>
</tr>
<tr>
<td>Butyl rubber</td>
<td>0.014</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 8.2: Comparison of stresses for different design iterations of the compliant bistable mechanism.

<table>
<thead>
<tr>
<th></th>
<th>Figure 8.5a</th>
<th>Figure 8.5b</th>
<th>Figure 8.5c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second stable position:</td>
<td>stress</td>
<td>12.1 MPa</td>
<td>12.2 MPa</td>
</tr>
<tr>
<td></td>
<td>deflection</td>
<td>22.65 mm</td>
<td>22.64 mm</td>
</tr>
<tr>
<td>Position where highest stress occurs during displacement:</td>
<td>stress</td>
<td>17.6 MPa</td>
<td>18.4 MPa</td>
</tr>
<tr>
<td></td>
<td>deflection</td>
<td>11.66 mm</td>
<td>14.5 mm</td>
</tr>
</tbody>
</table>

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Figure 8.5: Design iterations of the compliant bistable mechanism.

Figure 8.6: Comparing geometry of compliant segments. The thicker segments increase the force slightly.
which is an important characteristic for compliant mechanisms because it means the material will allow a larger deflection before failure [90].

The mechanism presented in this paper was designed to evaluate the performance differences between metallic glass (specifically, Vitreloy 1) and titanium (Ti-6Al-4V). The basic design for the bistable device is illustrated in Figure 8.2. The material properties for Ti-6Al-4V are $S_y = 825$ MPa and $E = 110$ GPa. The part was also rapid prototyped from extruded ABS as an early demonstrator of the model (see Figure 8.7). The relevant material properties used for the ABS design and analysis are $S_y = 36$ MPa and $E = 2$ GPa. The design parameters are listed in Table 8.3.

The bistability of the device is irrespective of the thickness of the material, but the actuation force is increased with increasing thickness (i.e., increasing compliant beam width). All designs were made for 3 mm thick sections. The shuttle should snap between two stable positions, with the second position bringing the shuttle just into contact with the base. Figure 8.2 defines the pertinent design parameters that can be changed or optimized to give a feasible design.

The compliant deflection was modeled using the pseudo-rigid-body model (PRBM), as shown in Figure 8.3. Figure 8.8 and Figure 8.9 show the predicted energy and force curves for the three designs, as determined by the PRBM. These models were then analyzed using finite element analysis and prototypes were fabricated and tested.

The finite element model for the bistable mechanism is a membrane model using ANSYS PLANE182 elements with mid-side nodes. The mesh, shown in Figure 8.10, was created by specifying the number of divisions along each of the lines in the model. The compliant
segments required a finer mesh because they will undergo large, nonlinear deflections. The outer geometry goes through less displacement and can therefore have a coarser mesh. The finite element analysis is displacement-controlled, where the total displacement was applied over 60-70 load steps, depending on which material is being modeled.
Table 8.3: Design parameters for the bistable mechanism prototypes, as illustrated in Figure 8.7 and Figure 8.11.

<table>
<thead>
<tr>
<th></th>
<th>Extruded ABS (Figure 8.7)</th>
<th>Metallic Glass (Figure 8.11a)</th>
<th>Titanium (Figure 8.11a)</th>
<th>Metallic Glass/Titanium (Figure 8.11b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>27 mm</td>
<td>10 mm</td>
<td>19 mm</td>
<td>11.5 mm</td>
</tr>
<tr>
<td>$l_s$</td>
<td>25 mm</td>
<td>13 mm</td>
<td>36 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>$l_c$</td>
<td>80.5 mm</td>
<td>30 mm</td>
<td>76 mm</td>
<td>55.25 mm</td>
</tr>
<tr>
<td>$l_b$</td>
<td>192.4 mm</td>
<td>74 mm</td>
<td>166 mm</td>
<td>129.6 mm</td>
</tr>
<tr>
<td>$t$</td>
<td>0.8 mm</td>
<td>0.5 mm</td>
<td>0.88 mm</td>
<td>0.88 mm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>80 deg</td>
<td>82 deg</td>
<td>82 deg</td>
<td>82 deg</td>
</tr>
<tr>
<td>$w_b$</td>
<td>78.5 mm</td>
<td>30 mm</td>
<td>34 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>$w_1$</td>
<td>5 mm</td>
<td>6.5 mm</td>
<td>6.5 mm</td>
<td>5.6 mm</td>
</tr>
<tr>
<td>$w_2$</td>
<td>6 mm</td>
<td>6 mm</td>
<td>6 mm</td>
<td>4.4 mm</td>
</tr>
<tr>
<td>$h_1$</td>
<td>10 mm</td>
<td>5 mm</td>
<td>5 mm</td>
<td>8 mm</td>
</tr>
</tbody>
</table>

Figure 8.10: An example of the finite element mesh for the bistable mechanism
8.4 Results

Several bistable compliant mechanisms were manufactured from titanium (Ti-6Al-4V) and metallic glass (Vitreloy 1) by wire-EDM [106]. The performance of the two materials was compared through two controlled designs shown in Figure 8.11. The main design parameters are listed in Table 8.3. In Figure 8.11a, the two mechanisms were manufactured to maintain the same safety factor, or same ratio of the yield strength to the maximum stress. This resulted in a titanium device that was more than twice as long as that of metallic glass mechanism due to the large difference in material properties. In Figure 8.11b, the two mechanisms were manufactured with identical geometries. The safety factor for the metallic glass mechanism is over two, while the safety factor for the titanium mechanism is equal to one. With such a low factor of safety, it is likely that the titanium mechanism experienced local yielding.

To compare performance, the identically sized titanium and metallic glass flexures (Figure 8.11b) were tested in a load frame to determine the force-displacement behavior. The results of the test are plotted in Figure 8.12, where it can be seen that the mechanisms do exhibit bistability with a clear intermediate instability point. The two materials exhibit roughly the same response because they have comparable stiffnesses, but the strength of the metallic glass is twice the strength of the titanium, thereby doubling its factor of safety.

Finite element analysis was used to verify and refine the design and to determine the maximum stress in the compliant members. The ANSYS finite element model consists of 10,000-20,000 PLANE182 elements, varying with the size of the mechanism. The mesh was refined along the compliant flexures and the motions were examined over 60-70 steps. The force on the end of the shuttle is calculated in the finite element analysis and plotted against the shuttle deflection in Figure 8.12. The FEA results predicted the bistable response, with force and displacement predictions accurate within 80%. The maximum stress in the finite element model was measured and is plotted in Figure 8.13. The yield strengths for metallic glass and titanium are indicated in the plot. This illustrates the difference in safety factors for the two materials with identical geometries.
Figure 8.11: Comparison of bistable compliant mechanisms prototyped from metallic glass and titanium. (a) Same safety factor. (b) Same geometry.

Figure 8.14 shows an example of the different stress states in the finite element model during the simulated displacement. The highest stress state (Figure 8.14b) occurs partway through the deflection, when the compliant beams are under a high compressive load.

There is a complex interplay between geometry and material properties that affect bistability. Table 8.4 lists the key parameters for bistability, which are all interdependent. The parameters $\theta$, $l_c$, $t$, $h_1$, and $w_1$ (as defined in Figure 8.2) all affect bistability and stress. Table 8.4 summarizes the effect of these parameters on bistability and stress. We defined an improvement in bistability as an increase in the force required to reset the mechanism from its second stable position to its first (as fabricated) position. As can be seen from the table, the dimensions $l_c$ and $t$ will be driven by the constraints of the manufacturing process and design space; optimizing the design will drive $t$ to its minimum thickness and $l_c$ to its maximum allowable length.

### 8.5 Applications

Compliant bistable release mechanisms can be used as non-explosive release mechanisms at a fraction of the cost and weight of traditional release mechanisms. Compliant bistable release mechanisms would eliminate the challenges of having explosive charges on the spacecraft.
Figure 8.12: Comparison of the force-deflection results from FEA and experimental testing for the mechanisms with the same geometry shown in Figure 8.11b.

Figure 8.13: The maximum stress in the identically sized mechanisms from Figure 8.11b, as predicted by FEA.
Figure 8.14: (a) Initial position of the finite element model. (b) Position where highest stress occurs during deflection. (c) Second stable position of the model.

They can be compact compared to other alternatives, thereby reducing weight. They will enable systems to be testable and resettable.

Other advantages of compliant bistable mechanisms are that they can accommodate integrated thermal actuation to change state and they only require power to change states, not to maintain state (this means much lower power requirements than many alternatives).

The technology developed to create these devices can be extended to other areas of space-related research, including gradient alloys, amorphous metals, and flexible electronics.

Flight applications for compliant bistable release mechanisms include deployable structures,

Table 8.4: Summary of how changes in the design parameters affect bistability and stress

<table>
<thead>
<tr>
<th>To improve bistability:</th>
<th>To reduce stress:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase $\theta$</td>
<td>Decrease $\theta$</td>
</tr>
<tr>
<td>Increase $l_c$</td>
<td>Increase $l_c$</td>
</tr>
<tr>
<td>Decrease* $t$</td>
<td>Decrease $t$</td>
</tr>
<tr>
<td>Increase* $h_1$</td>
<td>Decrease $h_1$</td>
</tr>
<tr>
<td>Decrease $w_1$</td>
<td>Increase $w_1$</td>
</tr>
</tbody>
</table>

*Approaches an asymptote
camera covers, launch locks, force sensors, maximum load indicators, and shutter mecha-
nisms.

A second application for metal bistable mechanisms are resettable joints to increase safety. When loaded past a predetermined force, such as in an unintentional impact, the resettable joint transitions to a second position and the load is immediately removed or the operator safely senses the event. It is analogous to an electrical circuit breaker in that it transitions to avoid overload, but can be manually reset after the event has passed. This joint is based on a bistable mechanism that is preloaded to a prescribed force. When the prescribed maximum force is exceeded, the mechanism switches to its second stable position. The preload stabilizes the mechanism for lower force inputs.

Another option for the resettable joint is to design a mechanism that is only nearly bistable, i.e., its force-deflection curve is similar to that of a bistable mechanism, but it does not have a stable second position. When an excessive load is applied, the mechanism will deflect into a second position; but once the force is removed, it will snap back into its original, stable position.

8.6 Conclusion

Compliant bistable mechanisms can be used in space applications as switches, latches, or relays, thereby eliminating friction and improving the reliability and precision of those mechanical devices. Such mechanisms could be integrated into deployment systems as non-explosive release mechanisms.

The finite element model was used to verify the pseudo-rigid-body model. The force on the end of the shuttle was calculated in the finite element analysis and plotted against the shuttle deflection in Figure 8.12. The curve illustrates the bistable nature of the device.
CHAPTER 9. CONCLUSION

The key contributions of this dissertation are: development of rigid-foldable methods for "winding-membrane" structures as deployable arrays, specifically focusing on a modified origami flasher pattern; investigation of actuation methods for the deployable array; development of a self-deployable map-fold array that is fully dense when folded; integration of deployable array and perimeter truss system; and design of bistable mechanisms in bulk metallic glass.

The deployable solar array, HanaFlex, employs a new method for deployment from a compact folded form to a large array. It also represents a rich area for future research regarding the joints and general assembly of the rigid flasher. By introducing the additional hinges along the diagonals of the panels, making all panels into triangles, the flasher model is rigid foldable. One of the unique features of this model is that the height constraints of the stowed array do not limit the deployed diameter. Additional rings can be added to increase the deployed diameter while only minimally increasing the stowed diameter. Larger solar arrays may enable longer missions in space, manned missions to distant destinations, or clean energy sources for Earth. The novel folding design of the HanaFlex array introduces many new possibilities for space exploration.

This dissertation has developed several approaches to accommodate thickness in origami-based deployable arrays with a high ratio of deployed-to-stowed diameter. A thickness-accommodating mathematical model was developed by Robert Lang to describe the flasher. Practical modifications were presented for the creation of physical models; namely, the panels are either allowed to fold along their diagonals or a membrane backing is applied with specified gaps between rigid panels at fold-lines. The mathematical model and hardware modifications were employed to create several physical models. Although the principles and approaches presented in this dissertation are general and apply to a range of possible ap-
applications, a motivating driver for this work was the development of a compact deployable solar array for space applications.

Several methods of actuation were developed for deploying the array. The research on actuation methods was focused on a one-time deployment of the array. Concepts for both passive and active actuation were considered. Once deployed, certain methods of passive actuation (such as centripetal acceleration and stored strain energy) may require an additional mechanism to lock the panels into their deployed state to keep the array flat. As uncontrolled methods of deployment are undesirable, such a latching mechanism is necessary to reduce the chance for failure with these methods of actuation.

During deployment testing, we observed that some of the actuation methods caused strong vibration loads on the panels. This was especially the case for the centripetal acceleration method and stored strain energy method, but was also observed to a lesser degree in the pneumatically actuated model. Further analysis and selection of final materials are needed to determine how detrimental these vibration loads will be to the structure and wiring.

Stowing the model is slightly more challenging; the folds could be constrained to only fold in one direction (mountain or valley) from the planar state. At least six actuation points are currently needed to prevent the panels from binding on each other during the transition to the stowed state.

CubeSats are the most likely avenue to launch a solar array using this origami-inspired design because CubeSat missions are relatively inexpensive. It is possible to launch the solar array as a technology demonstration mission, but it would also be desirable to team up with a group that has science they want to perform. Another option to consider would be to use the solar array in a satellite swarm to increase the power generation.

If thermal activation of a shape memory polymer can be achieved for in-space deployment, this method will be most promising for the CubeSat array. The actuation is slow enough to not induce vibration loads in the panels, and the material has a thin profile which takes up little of the constrained volume.

The origami flasher pattern was also applied in the folding of solar sails for two NASA CubeSat missions. Two methods were described for folding the sails: folding the quadrants individually while neglecting thickness, or accounting for thickness while folding the full sail.
Accounting for thickness increases the folding complexity substantially. If we are safely able to neglect thickness, then the difficulty level is comparable to other methods used, such as the z-fold on IKAROS [62]. Applying the flasher folding pattern to solar sails is advantageous because the deploying booms apply a tension that is largely perpendicular to the creases in the sail, which results in a flatter sail membrane.

This dissertation also includes the development of a compact, self-deploying array based on the tapered map fold designed by Charles Hoberman [3]. The key modification to the tapered map fold model is the application of an elastic membrane to one side of the panels, with adequate spacing between panels at valley folds, to create a self-deployable array. Potential applications for the array include a collapsible solar array for space applications, or military and backpacking applications. Future work will include quantifying the energy storage and rate of deployment for different membranes and layouts, and creating a working solar array prototype with crystalline silicon solar cells.

Some compliant mechanism design was done in support of the solar array design. This included a serpentine flexure to attach the array to the perimeter truss for deployment, and a bistable mechanism that may be used in the deployment of the array or sail. Compliant bistable release mechanisms can be used as non-explosive release mechanisms at a fraction of the cost and weight of traditional release mechanisms. They also enable systems to be testable and resettable, and can accommodate integrated thermal actuation to change state and they only require power to change states, not to maintain state (this means much lower power requirements than many alternatives).

The technology developed to create these devices can be extended to other areas of space-related research, including gradient alloys, amorphous metals, and flexible electronics. Flight applications for compliant bistable release mechanisms include deployable structures, camera covers, launch locks, force sensors, maximum load indicators, and shutter mechanisms.
REFERENCES


