# Deployment Methods for an Origami-Inspired Rigid-Foldable Array

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## 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 (Lang, 1997; Shafer, 2001). Figure 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 (Zirbel, Lang, Thomson, & al., 2013). The design of the array is novel and enables efficient use of space. 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.

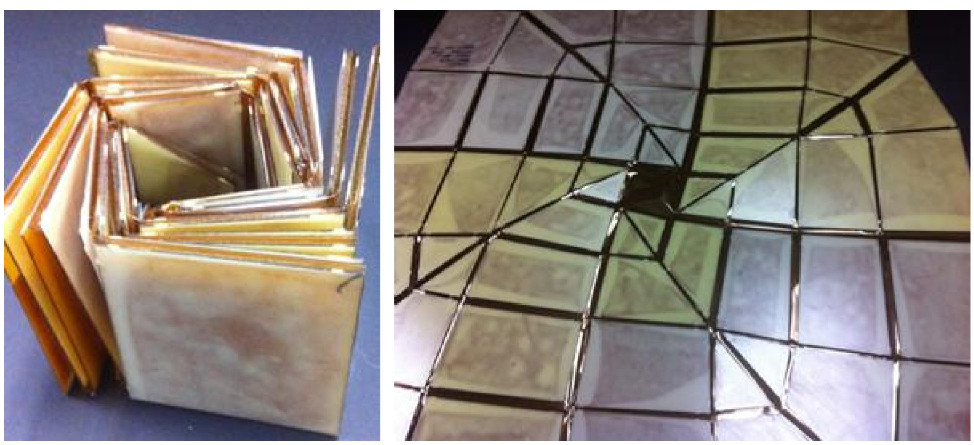

**Figure 1. (left) Folded form of the four-sided CubeSat array. (right) Deployed configuration**

## 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 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.

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Motor-driven perimeter truss

A scale model of an array and truss, shown in Figure 1, 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 deployment of the AstroMesh without motorizing the model.

**Figure 2. Partially opened model of the array and truss**

Torsion springs, shown in Figure 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. 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 point about 1.5 times to deploy the array.

**Figure 3. Torsion springs were affixed to the truss to bias the truss open**

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 4, to accomplish this rotation.

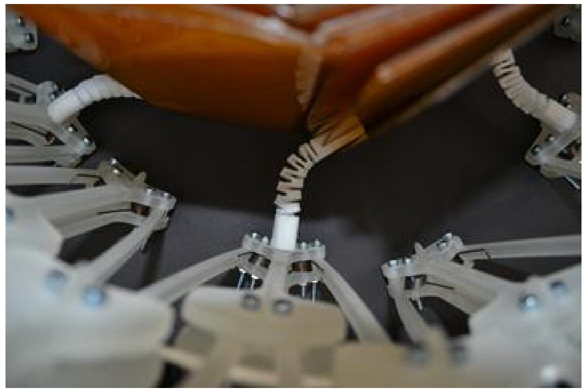

**Figure 2. Serpentine flexures enabled the complex motion needed to connect between the truss and the array**

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. In fact, it enables the two 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 5. 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.

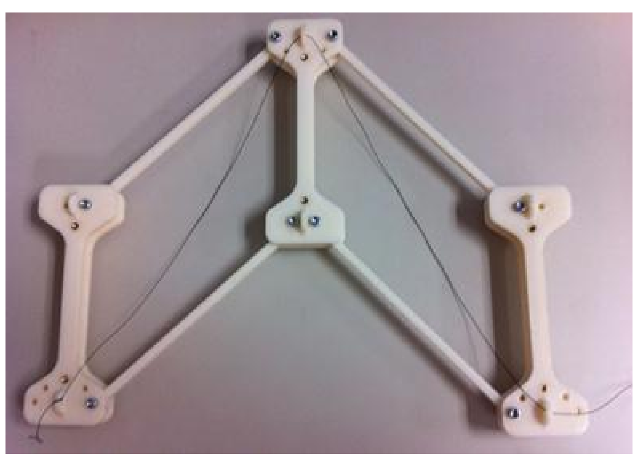

**Figure 3. Cable-driven actuation on a few bays from the square truss**

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.

Centripetal acceleration
Centripetal acceleration is the easiest to implement, as it can be accomplished by spinning the satellite. We demonstrated a concept for centripetal acceleration using a central torsion spring.

A torsion-spring deployer, shown in Figure 6, was prototyped to actuate the array. The array fits snugly over the small hexagon to hold it 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.

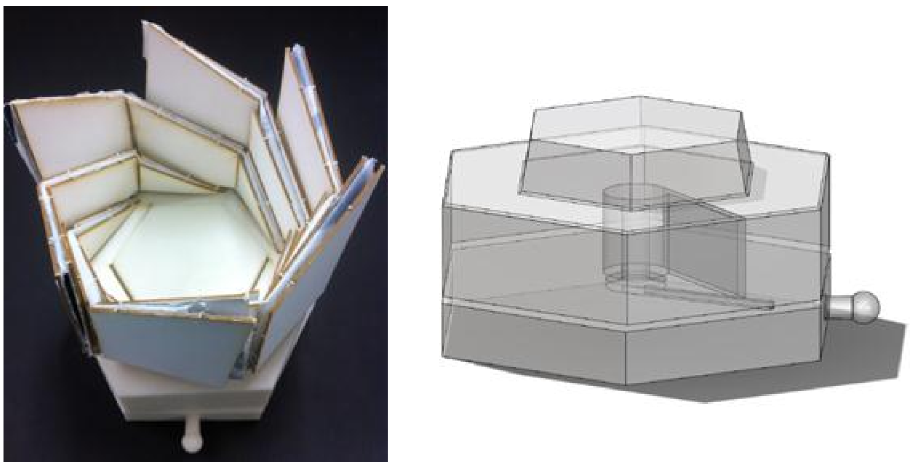

**Figure 4. (left) Prototype of the torsion spring test base with array. (right) Translucent rendering of CAD model, showing the cavity for the torsion spring**

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. 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.

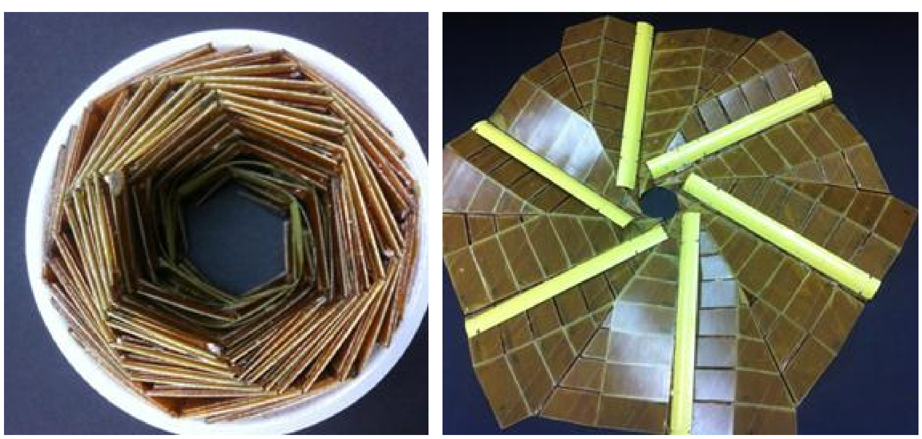

**Figure 5. (left) Stowed configuration of the array with radial tape springs. (right) Deployed configuration**

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-in) thick sheets of shape memory plastic as a means of actuating a deployable solar array, as can be seen in Figure 8.

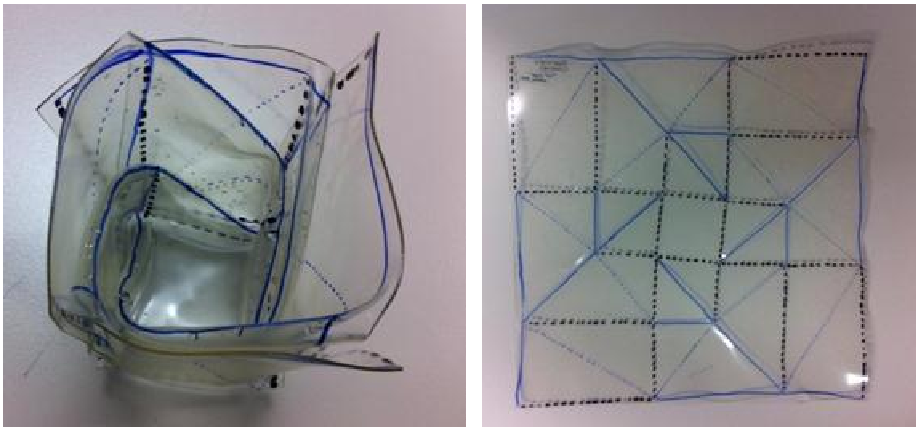

**Figure 6. (left) The shape memory plastic folded into a quad-flasher. (right) Deployed configuration**

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.

## 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.

## References


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Shafer, J. (2001). *Origami to Astonish and Amuse.* St. Martin's Griffin.

Zirbel, S., Lang, R., Thomson, M., & al., e. (2013). Accommodating Thickness in Origami-Based Deployable Arrays. *Journal of Mechanical Design,* Vol. 135, paper no. 111005, DOI: 10.1115/1.4025372.