Origami-Inspired, Re-Deployable, Compact Lunar Solar Array System

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Abstract

NASA is returning humans to the Moon and establishing a long-term presence near the lunar South Pole via its Artemis missions. To accomplish this, a reliable, sustainable power source is required to support lunar habitats, rovers, and construction systems for future robotic and crewed missions. To provide this power, NASA issued a solicitation for vertical solar arrays that can autonomously deploy and retract for relocation as needed.

Introduction

Under a Phase I SBIR NASA project, Folditure began using its existing proprietary pyramid hinge technology to develop a new 10-kW Lunar Surface Solar Array: the Sunflake Solar Array (SSA) and Ultra Compact Tripod Tower (UCTT). Folditure is currently working on a Phase II SBIR NASA project for the 10-kW Array, aiming to bring the design to Technology Readiness Level 5.

With a subsequent Phase I SBIR NASA project for a larger 50-kW Lunar Surface Solar Array (the Sunflake XL), a new dimension to the scalability of the design was introduced. Together, these innovations provide unique, origami-inspired solutions for elevated lunar solar array systems.

Requirements

Both projects require lightweight, robust, re-deployable solutions that are supported on a stable base structure and can accommodate a terrain angle of up to 15 degrees. Because of potential terrain shadowing, the bottom of the array needs to be 10 m above the lunar surface. To capture the optimum and consistent power supply, the Array assembly is required to rotate 360 degrees, tracking the sun.

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Pyramid Hinge

The Pyramid Hinge is an origami-inspired, mechanical solution that allows flat panel-based designs to unfold into rigid 3-dimensional structures. The patented mechanism was originally developed for applications in foldable furniture, where torque to open and close the structure was applied by hand.

Pyramid Hinge Array

The Pyramid Hinge Array is a combination of Pyramid Hinge units that are deployed or retracted by a central motorized movement. In the Sunflake design shown below, a runner mechanism (R) pushes or pulls a pyramid angle lever (PA1).

When approaching the open position, more force is exerted by the PA1 arm onto the PA2 angle, locking the array in place when fully open.

The three-dimensional “dead center” action of the opening geometry is a key feature of the Pyramid Hinge Array design. It assures that the array will always fully open and will easily retract.
During project development, it was discovered that in certain conditions the same origami-based geometry can be implemented using thin linear structural members instead of lightweight flat panels. With this added versatility, the Pyramid Hinge Array can be designed with varying numbers of subdivisions. It also can be designed to have a fully open position that is less than 360 degrees.

**XL Pyramid Hinge Array**

In the new XL mechanism, a single linear motion in all directions powers the deployment and retraction of the entire array. The same runner assembly that opens the array radially also extends and retracts the XL solar panel support arms. In the current design, three levels of the extension arm support three levels of folded flexible Solar Array gores, which overlap when stowed. The current design enables a 175-m$^2$ array to have a stowed length of only 2.6 m.

**Figure 4. Prototype Sunflake XL array shown only with outer panel assembly**

**Number of Divisions, Runner Lever Assemblies, and “Dead Center” Action**

The Sunflake design has a fully open angle of 360 degrees with three pyramid hinge segments, making the PA angle (Figure 2) 120 degrees. The Sunflake XL has a fully open angle of 342 degrees with six pyramid hinge segments, making the PA angle 57 degrees.

The linear force applied to the runner assembly applies differently to the opening movement of the two designs. This is from the difference in PA angles, plus the different lever assembly designs. While enough force will always be available to lock the Pyramid Hinge Assembly in the fully open position, some initial force (other than the runner movement) might be needed to “pry” the array arms open a few degrees. This can be provided either by slight spring action, with lunar gravity (as in the case of the Sunflake Array design), or with a specially shaped runner mechanism that can pry the arms slightly open.
Overall Design and Deployment Sequence

The Sunflake/UCTT assembly was adapted to work with the Astrolab Lunar Rover, creating a comprehensive deployment, retraction, transportation, and storage solution. The flat, compact design enables four Sunflake/UCTT units to be transported and deployed by the rover.

The UCTT was designed to provide a stable base for the Sunflake Array and allow space for the rover to maneuver underneath.

In the current design, four Sunflake/UCTT assemblies fit within a rack called the Sunflake Deployment System (SDS). The SDS is designed to meet the requirements of the Astrolab Rover front load payload. Because the rover can maintain a horizontal position on uneven terrain, the UCTT deploys vertically.

First, the mast lifts the UCTT above the rover, then it is deployed using a three-segment pyramid hinge array (similar to the Sunflake design). As it deploys, it positions three telescoping leg assemblies to a fixed angle, and the legs extend until they touch the terrain surface (Figure 7). The mast then moves in the opposite direction, lifting the Sunflake array out of the SDS assembly.

Once the legs are deployed and the Sunflake clears the SDS and rover, the rover can move out of position. The Sunflake array continues lifting, opening once it clears the UCTT leg structure and reaches its deployed position (Figure 8).
A key component of this system is a robust, lightweight mast mechanism that can move in two directions. It moves in one direction to lift the UCTT, as shown in Figure 7, then it changes direction and lifts the Sunflake array, as shown in Figure 8. The novel gear and chain drive design, that helps the mast accomplish this, was implemented in the ¼-scale prototype. Figure 9 shows part of the chain drive with the UCTT partially deployed.

The larger ½-scale prototype creates a lighter, more scalable solution by using a mechanism that combines the chain drive with cables (Figure 10).
This new mast mechanism can have three or more linear components. While the driving chain is on the middle component in the current design of the \( \frac{1}{2} \)-scale prototype, it can be positioned on any of the components. A great benefit of this mechanism is that the cable/harness can follow the same movement as the cable. The cable length is fixed, and there is no risk of stretching or entanglement.

Combining the Pyramid Hinge Array geometry with linear expanding structural members yields a compact, lightweight, and robust solution for providing solar power on the lunar surface. The current design performance is: 55.56-kW/m\(^3\) specific packing volume and 107.85-W/kg specific mass including all mechanical and electrical components. This exceeds NASA's requirements as stated in the solicitation.

**Conclusion**

The final Phase II SSA/UCTT design will have a 10-kilowatt capacity, and is engineered for deployment on the Moon with sun-tracking capability for optimal energy capture. When fully deployed, the structure will reach approximately 14 meters in height, including the mast.

**Technology advantages over state of the art:**

- The Sunflake Solar Array designs can easily be adapted for deployable arrays in microgravity and could be used on any mission that requires lightweight portable high-efficiency energy, including use on any form of human lander, future lunar outpost, or orbital station.
- The mast design is simple, robust and could be used at a much larger scale.
- Folditure's technology represents a shift in foldable solar array design, featuring compact folding and automated deployment, retraction, and re-deployment capabilities.
- The mechanisms are covered by existing and pending US patents.
- The technology can be manufactured using standard materials and manufacturing processes.

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