The Light Bender Concept for Power Distribution on a Lunar Base

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Power generation and distribution is a challenge for a future lunar base. A promising concept for lunar power distribution is the Light Bender—a system that utilizes autonomously deployed mirrors to reflect sunlight to shaded regions on the lunar surface. The Light Bender system consists of two components: tandem reflector mirrors (TRM) which reflect sunlight to a permanently shaded region and the Cassegrain Fresnel distribution optics (CFDO) which collects the reflected light from the TRM and redirects light to local consumer nodes. This paper describes the Light Bender system concepts and the associated system analysis and technology development performed as part of a 2021 NASA Innovative Advanced Concepts (NIAC) phase I award.

I. Introduction

NASA's plans for future lunar exploration call for the establishment of a small base near the South Pole of the Moon. One requirement of a lunar base is that all key mission nodes (e.g., habitats, landing sites, and in-situ resource utilization (ISRU) elements) need to be supplied with an adequate supply of electrical power. Investments in lunar power generation have been focused on both solar voltaic cells and nuclear generators, but both of these technologies require extensive power distribution systems.

One such power distribution system that has been studied is DC power transmission via transmission lines [1–3]. This high technology readiness level (TRL) solution provides a very high efficiency in power transmission—in excess of 85%. This high efficiency minimizes the amount of additional power needed to be generated in order to adequately supply the lunar base. However, this high efficiency comes at the cost of mass and operability; power cables require between 0.4 and 1 kg/m of landed mass [2], and these cables must be deployed across uneven terrain on the lunar surface.

Another option that has been studied for power distribution is laser power beaming [1,2]. These lower-TRL systems would avoid the operational difficulties of laying power cables on the moon because hardware can be landed

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at the power generation site or the power consumption site. However, this power distribution system is approximately 21% efficient because electrical energy must be converted into light power and back into electrical power by photovoltaic cells at the destination [2]. This inefficiency leads to a much larger amount of power generated compared to power cables to supply a similar amount of power. Ultimately, laser power beaming ends up being a more mass efficient solution compared to power cabling at distances greater than 6 km [2].

In order to address these shortcomings in power generation and distribution, the Light Bender is a proposed concept that redirects sunlight to shaded areas of the lunar surface so that photovoltaic cells at key mission nodes generate power locally. This concept avoids the mass penalties of power cables and the inefficiencies of laser power beaming. In addition to providing these operating efficiencies, Light Bender also provides two less easily quantifiable mission benefits. First, Light Bender allows for the distribution of power to areas where cables cannot be pulled such as a crater floor. Second, the system creates a truly "wireless" and dynamic power grid architecture that can be reconfigured based on emerging needs of the growing settlement. In recognition of Light Bender's promise, the concept was awarded a 2021 NASA Innovative Advanced Concepts (NIAC) Phase I award; this paper documents studies performed as part of this program.

II. Component Designs

A. General Concept:

Light Bender is an optical system designed to distribute sunlight on the lunar surface for distances approaching 5km while maintaining sufficient beam integrity to generate power photovoltaically at the destination. The purpose of the system is to create a dynamic power distribution system capable of transferring light energy to end users without cables or the multiple conversions of light to electricity required in a laser power beaming system. The system has three main components. First two large (~10m diameter) flat mirrors are used in tandem to collect and redirect sunlight to a distant receiver. A second optic system based on a Cassegrain design receives this redirected sunlight, focuses the beam, and further redirects the light to an end user. Finally, each end user will be equipped with a photovoltaic receiver panel that will convert the light into electricity at the point of use. The development of the Tandem Reflector Mirrors and the Cassegrain optics are the focus of the Light Bender project and this paper. It is assumed that all assets operating on the lunar surface will be designed with a photovoltaic receiver.

B. Tandem Reflector Mirrors

The Tandem Reflector Mirrors (TRM) are basically a heliostat (Figure 1). The mirrors are deployed on a 10m mast and operate in tandem to collect sunlight and redirect that sunlight into a lunar crater or permanently shaded region (PSR). Although working in concert, these two mirrors function independently. In the concept depicted in Figure 1 the lower mirror is tracking the sun over the 28-day lunar cycle. The upper mirror continuously modifies its position such that it reflects the light coming off of the lower mirror onto a target. The target of the TRM reflection is the second component of the Light Bender system, the Cassegrain Fresnel Distribution Optics (CFDO). It should be noted that this can function in the reverse order, i.e., the primary collection takes place on the top mirror and the redirection to the target would be done by the lower mirror. The decision on operation will be made after further analysis of the availability of continuous sun light in any given location and the degree of difficulty involved in reaching the CFDO via the lower mirror. There is no reason that this decision must be made until the assets are in place, in effect making it a "Game Time Decision".

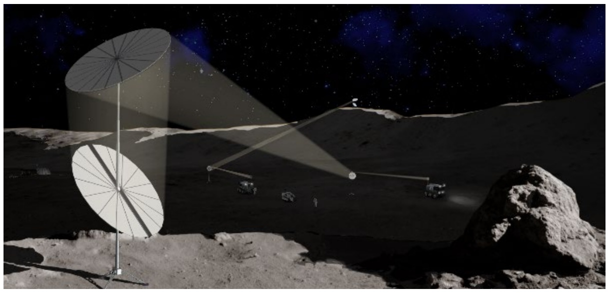

Figure 1. TRM Illustration

The TRM will be composed of the mirrors, mast, and control electronics necessary to operate autonomously for extended periods of time. More importantly, the component will be designed for delivery to the lunar surface in a small purpose-built lander similar to the Commercial Lunar Payload Service landers under design and development by commercial entities for NASA. Early design metrics call for a mass of less than 250kg and the ability to pack and stow in a volume of less than 10m^3.

C. Cassegrain Fresnel Distribution Optics (CFDO)

The CFDO component to Light Bender can be further subdivided into two main sub-systems, a Cassegrain primary mirror that collects the light beamed from the TRM and a periscope assembly with an embedded Fresnel lens which focuses and redirects the light to an end user (Figure 2). The two components are designed to act independently. The primary parabolic dish remains focused on the TRM light beam, and in situations where there are multiple TRMs the dish will have the capability to rotate to collect light from any source available. The periscope assembly with the embedded Fresnel lens then focuses the light further and can redirect the light in both elevation and azimuth towards a designated target consumer. Similar to the TRM, the CFDO will be designed to function autonomously and to be packaged in a small lander for deployment on the lunar surface.

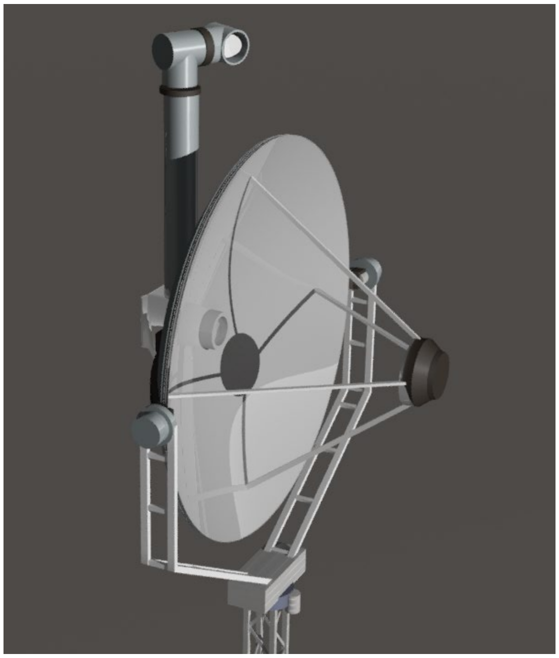

Figure 2. CFDO Illustration

III.Concept of Operation

A. Deployment

The Light Bender system is designed for autonomous deployment via small purpose-built landers. It is assumed that the deployment of the TRMs will occur in elevated terrain to maximize the opportunities for continuous sunlight to strike the primary collector with a minimum of terrain shadowing effects. There is also a possibility that the CONOPS may eventually involve the use of multiple TRMs to minimize the effects of intermittent shading at any one location. In such a situation, the multiple TRMs will be positioned such that the chance of shading of all assets at any time during the lunar cycle is prohibitively small. The CFDO component of Light Bender will be deployed in or near a PSR. The actual landing spot of the CFDO may or may not be a “local maximum” in elevation as flatter terrain will be the most likely landing spot. The CFDO must have a direct line of site to the TRMs and receiver elements located at end users. Given the need for multiple landers and operating assets, the size of each component (mass and volume) remains of paramount concern to the design team. These elements will be addressed in greater detail in the following sections.

B. Operation

The Light Bender will function autonomously. Upon landing the system will initiate a deployment sequence after initial communications with the mission control function are established. This deployment will then proceed autonomously resulting in the deployment of the 10m mast and the unpackaging/deployment of the primary mirrors and associated sub-assemblies. After full deployment the CFDO and the TRM will establish a communications link that will allow them to direct the light from the TRM to the CFDO. In a similar fashion the CFDO will establish links with end users such that light can be redirected to individual receiver elements. At this time, it is envisioned that most, if not all, of the assets operating in the PSR will be unmanned and therefore autonomous interaction will be required. The TRM system will track the sun and continuously compute the necessary mirror changes required to keep the CFDO in the projected spot beam.

C. General Performance

The Light Bender system contains 6 mirrors and 1 Fresnel lens. The TRM consists of two flat mirrors of 10-meter diameter to collect and redirect the sunlight. A 10 m diameter parabolic mirror with a -4.94 m radius of curvature (ROC) is the primary mirror of the CFDO. A 0.80 m diameter concave mirror of 0.37 m ROC is the secondary mirror within the same sub-system. Two additional flat mirrors of 4.00 m diameter are used within the CFDO periscope. These mirrors will be made with ultra-lightweight substrates that are well polished and coated for highly reflectivity ($R \geq 95\%$). The Fresnel lens is a 3.00 m diameter, 0.20 m thick and 5.70 m ROC optic made from a high solar spectral transmission material. The input face has concentric gratings of one line per millimeter density. The substrates and the reflective coating on the mirrors will be capable of withstanding the lunar environment as well as micro-meteor impacts.

A Zemax optical design model predicts that the Light Bender system described above can redirect the solar beam in any direction from its location. It shows that when the sunlight is redirected at a 90° azimuth from its initial direction using a single flat mirror, 1.6 kW of solar power can be transmitted to a 6 m diameter dish located 5.5 km away, and the transmitted power increases as the redirecting angle becomes more acute. When two flat mirrors are combined for redirecting the sunlight, the transmitted solar power reduces to 1.2 kW when the both mirrors are tilted by a 45-degree angle with respect to the direction of the incident beam. However, that power will also increase when the reflection angles are acute.

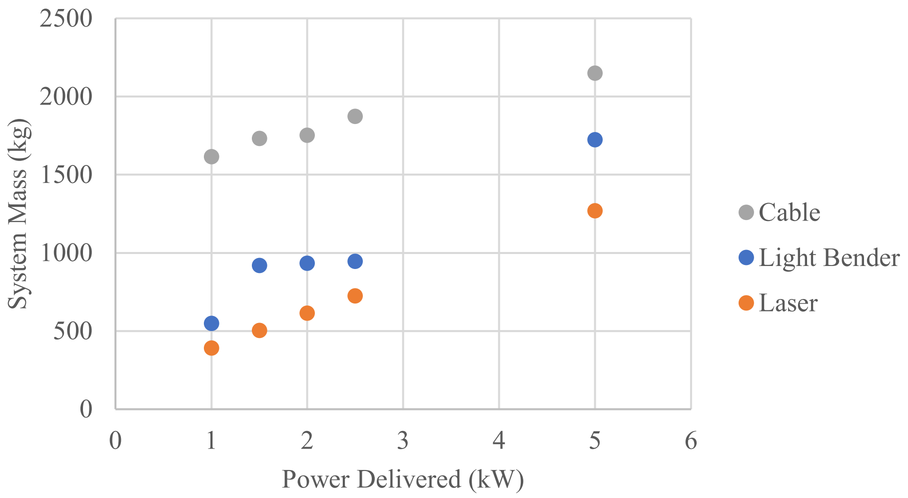

Figure 3. Scenario 1 Results

D. Systems Analysis

Additional systems analysis is performed to estimate the mass of the Light Bender system and compared to competing power transfer systems. For the systems analysis, the mass is estimated for the TRM, CFDO, and the photovoltaic receiver system located at the consumer node, which includes a thermal control system and a solar array voltage output regulator. The number of TRMs is scaled such that Light Bender is able to provide a specified amount of power. When multiple TRMs are required, they are spaced along an arc with 5° between them. The CFDO parabolic primary mirror is then angled to point at the center of the arc of TRMs. The Light Bender system mass is compared to DC power cables and a diode laser [2].

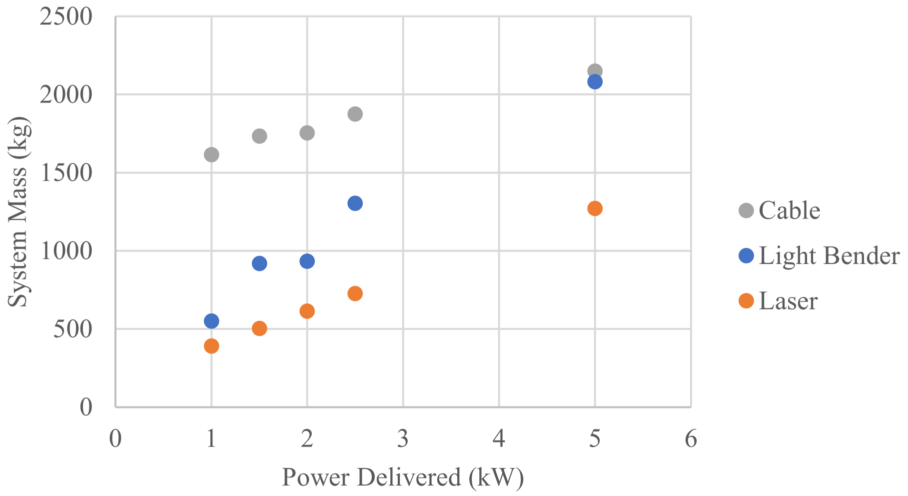

Figure 4. Scenario 2 Results

As part of the systems analysis, three scenarios were investigated. Scenario 1 has a total transmission distance of 3.5 km. For Light Bender, the TRM and CFDO are located 3 km apart from each other and the CFDO is 0.5 km from the receiver. The sun is at an angle of 0° and the angle between the TRM and CFDO is also 0°. The CFDO and receiver are assumed to always be horizontally separated and have an angle of 0°. The power requirement ranges from 1 kW to 5kW.

Scenario 2 also has a total transmission distance of 3.5 km. In this case, the angle between the TRM and CFDO is now changed to 15°, meaning the light beam is angled 15° below horizontal to travel from the TRM to the CFDO. While the angle of the mirrors reduces the transmissible power for Light Bender, the cable- and laser-based systems do not have any loss in performance.

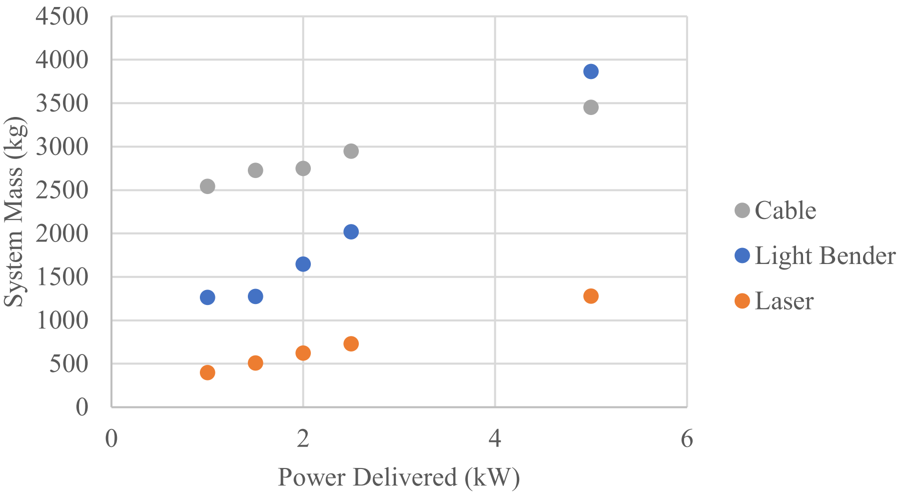

Figure 5. Scenario 3 Results

Scenario 3 has an increased total transmission distance of 5.5 km. The TRM and CFDO are now located 5 km apart, while the CFDO and receiver remain 0.5 km from each other. The entire system is again assumed to operate with 0° angles as it did in scenario 1.

Figure 3, Figure 4, and Figure 5 show the outcome of the total system mass comparison for the three different systems. The mass of Light Bender is less than the cable system for all but one value and greater than the mass of the laser system. This initial systems analysis shows that the Light Bender concept is comparable in mass per electrical power delivered to other power distribution concepts. Further studies which specifically trade the operational figures of merit are needed to examine the tradeoffs between the autonomous deployment of Light Bender with other systems that will need to be assembled on the lunar surface.

IV. Technology Development Challenges

As part of the NIAC award, three areas of technology development are being explored. The first is further development of the system's optical design. The second area is the concept for autonomous deployment. The deployment requirements have led to the exploration of utilizing shape memory alloys (SMA) for the primary mirror.

A. Optical Development

There are several challenges in developing the optical system for Light Bender. Chief among these is creating reflective surfaces and structural components for both the primary mirrors of the TRM and CFDO systems. Ten meter mirrors in and of themselves would not be a challenge in a terrestrial setting, but designing mirrors that can be segmented or folded for a launch package is considerably more difficult. In the sections below several of the mirror designs and packaging concepts will be discussed, but throughout the discussion it must be remembered that optical performance remains a key element of success.

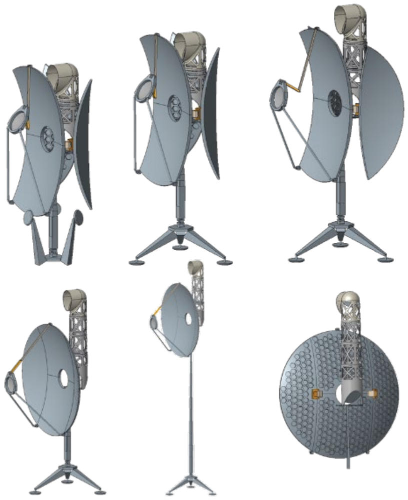

Figure 6. CFDO Baseline Concept

Beyond the large mirror optical/packaging issues lurks another design issue that is very important to ultimate success: the transition of the optical beam from a direct beam reflection of the TRM to a beam that is manipulated and redirected by the CFDO's periscope complex of Fresnel Lens and flat mirrors. It is at this point where the Light Bender system shows its true value. This periscope assembly effectively creates a dynamic power distribution hub wherever it is deployed. Although technological analogues exist, it will be a requirement of this project to develop a workable sub-system that displays these characteristics and to demonstrate the effectiveness of the beam movement in testing.

B. Autonomous Deployment

Autonomous deployment is achieved through a combination of structural components and mechanisms. The deployment towers of both the TRM and CFDO are based on a known design for an autonomously deployable 10m mast developed at LaRC for the Vertical Solar Array Technology (VSAT) project. This base concept may be revised/optimized as Light Bender design requirements are better understood. Overall optimization of the complete system, and its complexity, are driven by the vehicle on which it is transported on and the envelope it must fit into.

Figure 7. CFDO Alternative Configuration

1. *Initial Mirror Designs*

It was recognized early on that both the collection and distribution system of the TRM and CFDO would be composed of folding and/or telescoping structures. The 10m mirrors of the TRM can be deployed in a similar fashion to radial folding solar arrays. The smaller parabolic mirror of the CFDO can simply be folded at strategic locations upon a hinge line to be stowed similar to other dish style antennas. Using the VSAT mast design, the periscope extension was also believed to be a solvable problem that would not impinge on optical efficiency. Although significant work remains to actualize these design concepts the issues do not seem insurmountable. This leaves the one very difficult optical design/packaging problem in front of the team and this is how we design the primary mirror of the CFDO for packaging.

In order to minimize the stowed volume of the Light Bender system, multiple packing methods were considered for the primary mirror of the CFDO. The baseline packing and deployment method, shown in Figure 6 utilizes hinged sections to fold the parabolic mirror, giving a baseline for system mass, stowed volume and optical efficiency. An alternative configuration, seen in Figure 7, was examined that uses a flexible reflective material such as Mylar held in shape by umbrella-like ribs. This method offered a lower system mass and stowed volume, but a reduction in optical efficiency inversely proportional to the number of ribs. In order to maintain optical efficiency, another alternative was considered which divides the rigid parabolic mirror into 20 radial sections. To deploy the mirror, these sections fold outward and twist along their long axis as shown in Figure 8. This method yields an improved stowed volume to the baseline at a comparable mass and optical efficiency, but the biaxial rotation in deployment adds complexity.

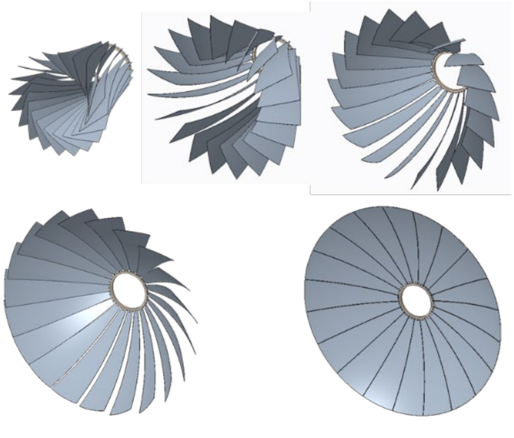

Figure 8. Biaxial Rotation Deployment Sequence

2. *Shape-Memory Alloys*

SMA actuation was suggested as a potential alternative to a purely mechanical deployment scheme. SMAs exhibit a diffusionless, solid-state phase transformation between a lower-symmetry microstructure (martensite) and a higher-symmetry microstructure (austenite) in response to changes in temperature and applied stress. Significant changes in many properties and useful behaviors accompany the phase transformation. The behavior of most interest for this application is known as the shape memory effect (SME).

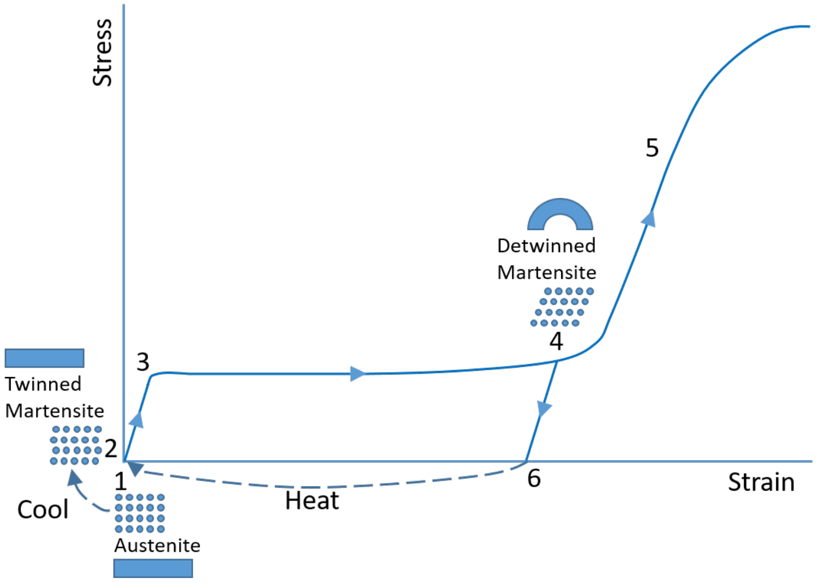

Figure 9. Shape Memory Alloy Performance

The SMA is demonstrated in Figure 9. The component is heat treated (shape set) to a unique configuration at high temperature in the ordered austenite phase; see condition 1 in Figure 9. The component is then cooled to transform the microstructure to the lower-ordered martensite (condition 2). Light applied stress easily deforms the material by reorientation of martensite variants (detwinning) to large strains (condition 4). Unloading the component is accompanied by recovery of elastic strain (condition 6), but the transformation strain remains until the component is heated to return the microstructure to austenite and the reference configuration (condition 1).

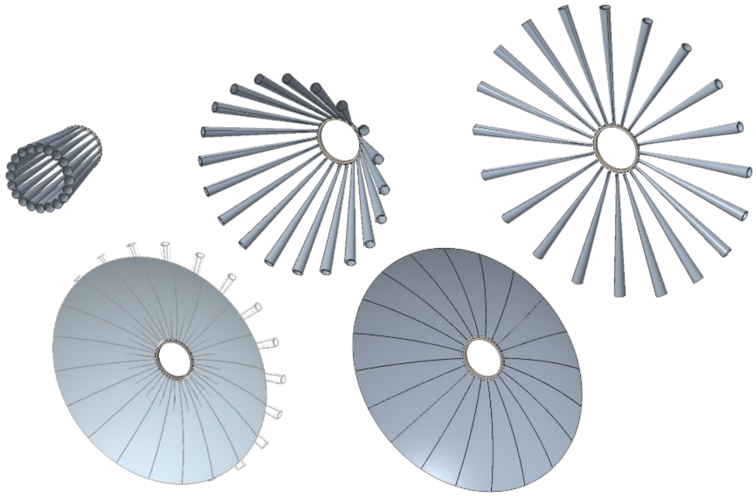

Figure 11. Long Axis SMA Deployment

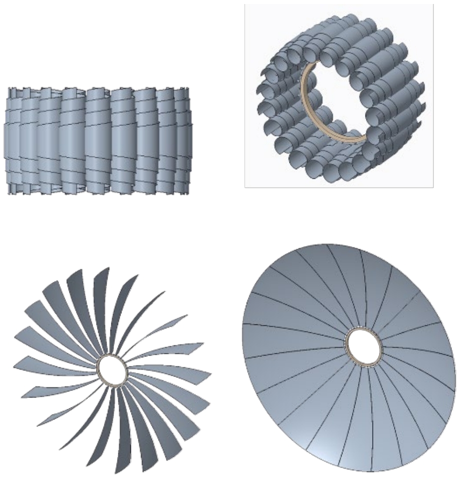

Figure 10. Short Axis SMA Deployment

In this concept, the parabolic mirror is divided into 20 radial sections of SMA material, each shape-set to its final deployed parabolic shape. Each section is then rolled into a cylinder along either its long axis (Figure 10) or short axis (Figure 11). When the CFDO is deployed, the mirror sections are reheated to their transition temperature and unroll into their parabolic shape. It is anticipated that constructing the parabolic mirror out of sheets of SMA material will enable a lower mass and stowed volume, however there are various questions to be investigated to determine the suitability of SMA for this application.

The primary factors which will need to be quantified to determine the suitability of SMA for the Light Bender primary mirror are the following:

- Which packing method (short-axis fold or long-axis fold) offers the better stowed volume and deployment reliability?
- How reliably can the SMA sheets return to their trained shape in the lunar environment?
- How stable is the shape of the SMA mirror when in use at lunar temperatures and during intermittent periods of shadowing?

- Which alloy is optimal for the Light Bender use case involving a single deployment in lunar polar environment?
- Can solar heating be employed for deployment of the mirror or is applied heating required?
- What are best practices for producing a highly reflective, specular surface on the SMA mirror segments?

Benchtop coupon testing will be performed in order to address these questions. A shaping die (Figure 12) has been acquired which will be used to shape SMA coupons into a scale parabolic section. Each coupon will be held in the die and immersed in a liquid salt bath to set the deployed shape. Cyclic stow-deploy tests will be conducted via applied heating to study deployed shape accuracy and microstructure evolution. Surface preparation for the reflective surface will also be studied by leveraging previous work [4].

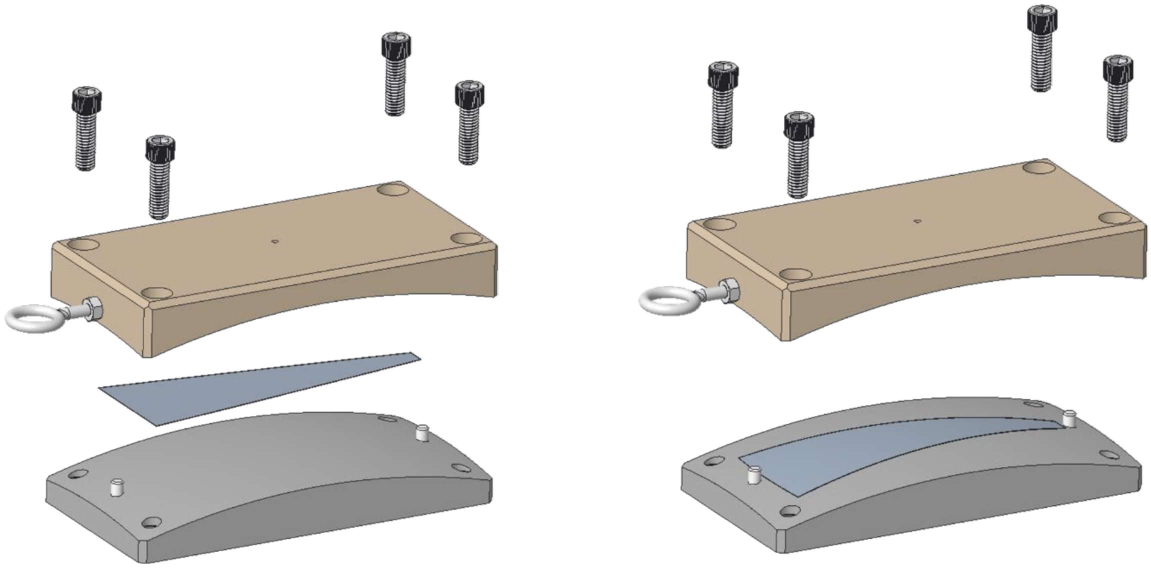

Figure 12. SMA Shaping Die

V. Conclusion

The current work being performed as part of the NIAC phase I award is focused on maturing the Light Bender power distribution concept and its constituent technologies. Systems analysis has shown that this concept is competitive with established power distribution concepts for a lunar base while having the advantage of fully autonomous deployment. This autonomous deployment is enabled by SMA mirrors. Continued development of this concept will realize the potential of truly wireless power distribution on the lunar surface to support the initial settlement of a lunar base.

Acknowledgments

The authors would like to thank Ron Neale of NASA Langley Research Center for creating much of the artwork used in this paper.

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