HuLC Smash

Ohio Northern University

Team Members:

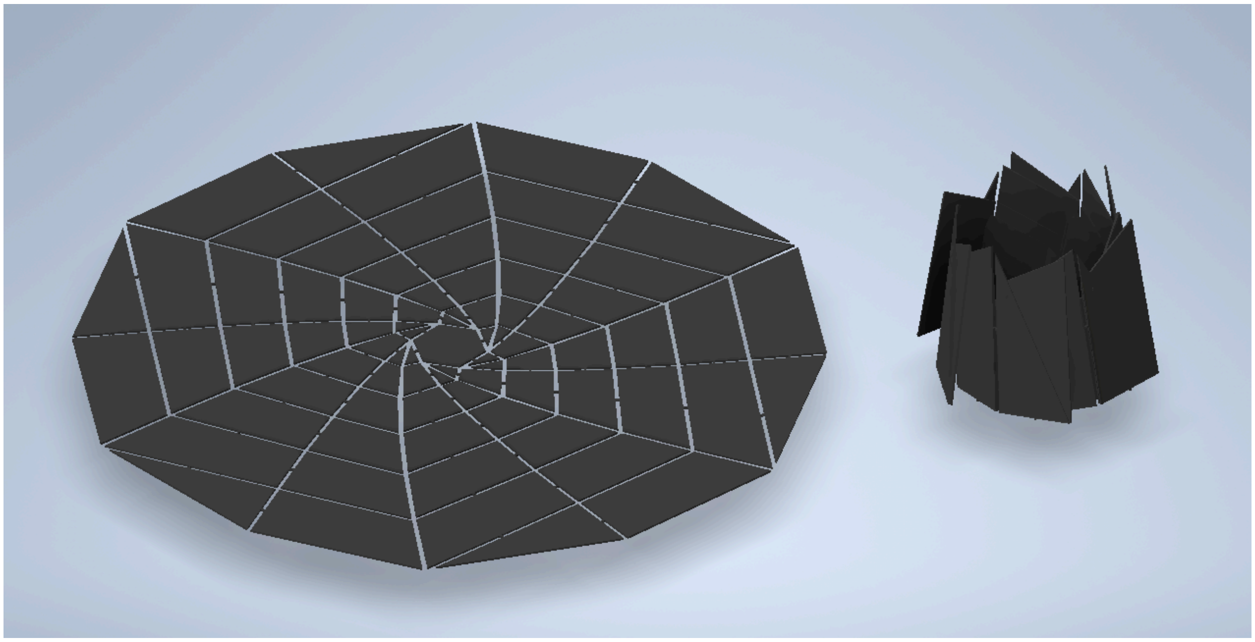
Harper Flynn: Undergraduate Mechanical Engineering, Class of 2024

Jadon Brownlee: Undergraduate Mechanical Engineering, Class of 2025

Noah Daugherty: Undergraduate Mechanical Engineering, Class of 2024

Xavier Disney: Undergraduate Mechanical Engineering, Class of 2024

Faculty Advisor: *Dr. Louis DiBerardino*, PhD, Associate Professor of Mechanical Engineering



Ohio Northern University – HuLC Smash

Major Objectives & Technical Approach

- Our main objective is to prevent the plume from having a chance at interacting with the lunar environment.
- This system will physically block the plume using heat-resistant carbon fiber composite.
- The pad is based on the geometry of the *Starshade* system.
- Utilizes its own kinetic energy to function.

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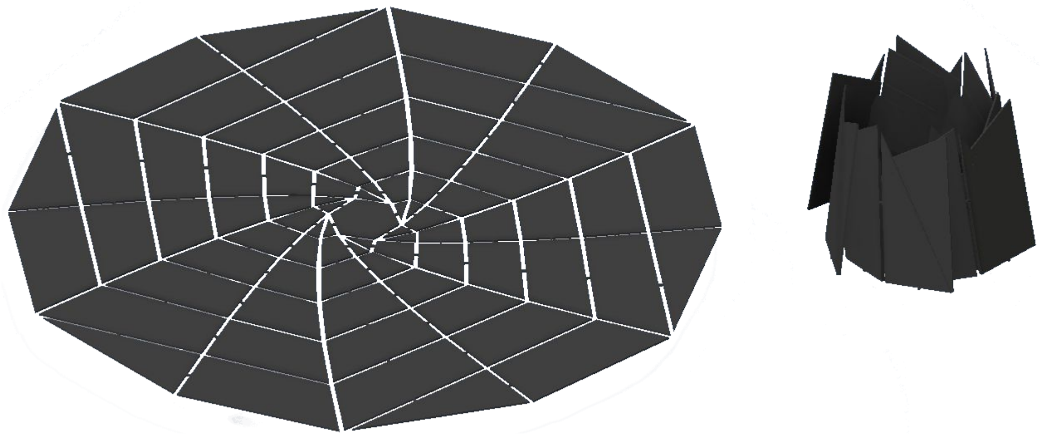

Key Design Details & Innovations of the Concept

- Utilizes an origami “flasher” pattern to simplify transporting a full-sized landing pad.
- This design is far less complex than existing lunar pad concepts in addition to being far easier to adopt.
- Requires only a single landing before Artemis III.
- Single-use nature means system / procedure is inexpensive

Summary of Schedule & Costs for the proposed solution’s path to adoption

- Schedule – After the competition, assuming selection, it would be a fast process to refine or modify any of the geometry to make it more compact / lighter. From this point, manufacturing and testing can be estimated to be done within the 3-5 year period. By the time Artemis III is ready, the system should be ready for use.
- Costs – Using NASA costing tools, an estimated material price for the construction of a pad is about $4.5 million. With multiple test variants, labor, and test equipment, an estimate for development and production is around $10-15 million.

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Problem Statement & Background: The category that our proposed design sets out to address is that of *Reduction and Mitigation of Erosion and Ejecta During Descent, Landing, & Ascent*.

The method that HuLC Smash proposes to address this issue is through the use of a folding landing pad. This design is heavily influenced by the *Starshade* folding mechanism. The concept of using an origami flasher-inspired pattern means that the landing pad can be efficiently stored in the cargo compartment of a transport rocket and then be expanded to an appropriately sized flat pad once deployed in order to block the rocket exhaust from interfering with the lunar surface. Strong, flexible Kevlar hinges running the length of the seams will work to prevent dust from being shot up between the panels while allowing them to flex with little resistance during deployment. This is also made possible by the massive cargo capacity of most modern rockets, both volumetric and mass-wise, including the Falcon Heavy being able to carry 16 tons. Using modern high-strength materials such as carbon fiber composites in conjunction with being supported by the ground beneath, the folding pad can be both thin and lightweight for its size and for the cargo capabilities of the rocket that would deliver it to the surface. The heat resistance would be provided by a layer of ceramic shielding similar to that on the space shuttle.

The HuLC Smash team's landing pad system would be attached to the bottom of a rocket for deployment onto the lunar surface, much like how the Perseverance Rover was deployed on Mars. The rocket would release the pad mechanism in its furled state during a hover near the surface of the moon similar to how the rovers are lowered to the surface of Mars. The pad, unlike the deployment of the Perseverance Rover, would be subject to free-fall, from which the deployment rocket would accelerate away and land at a safe distance from the HLS landing zone as to not be a potential hazard to the lander.

This device plays a crucial role in meeting the requirements of the PSI mitigation category it aims to address. The prevention of exhaust impingement onto the lunar soil means that there is no abrasion to any components on the actual lander and the landing sequence and landing zone are safer due to there no longer being a dense cloud of regolith particles. The sensors used for landing would be able to see the ground unabated.

In reference to NASA's Plan for Sustained Lunar Exploration and Development, we aim to undertake the portion of the *Lunar Surface Innovation Initiative* that is *lunar dust mitigation*, in which that document highlighted this as important from the start of our return to the moon and subsequently will allow the other operations to go smoother. Our method of preventing exhaust impingement means that the planned surface-based establishments, being habitation modules or rovers and other vehicles, will not be subjected to nearly as much of the harmful high-velocity ejecta caused by descending upon typical unprepared lunar landing zones.

Project Description:

Design Description

The specifics of the landing pad are as follows. The current design of the pad is a 60-ft diameter dodecagon that is segmented into parts following a pattern much like that of the *Starshade*. A dimensioned drawing of the prototype can be seen in *Appendix A*. Each segment is a 1 inch thick panel of carbon fiber composite material that has a protective coating of thermally resistant ceramic in order to resist breaking down due to extreme exhaust temperatures. The panels are able to be relatively thin due to the support offered by the ground underneath. These panels will be bridged by Kevlar, as it will perform with high tensile properties under both extreme high and extreme low temperatures. The segments allow the pad to fold into a cylindrical shape, greatly reducing the diameter (up to 5 times smaller in testing). A central fluid reservoir will contain a working fluid that will be pumped out to actuators on the outer region of the pad to push the panels apart to unfold the pad. The HuLC Smash team has elected to take advantage of the compressibility and overall inertness offered by the use of a noble gas as the working fluid in this application. The compressibility of the gas would offer some reduction in the amount of shock absorbed by the structure of the pad, greatly increasing the likelihood of it surviving its deployment onto the lunar surface and performing as intended. With the pad being a single use technology that is to be completely unfurled by the time the landing module is set to make contact with the lunar surface, heat shielding on the central reservoir is not necessary. This makes the possibility of the containment of the working fluid within the central reservoir to be compromised, releasing the working fluid into the lunar atmosphere. The use of a noble gas is, therefore, imperative to the success of the overall mission to not contaminate the surrounding lunar environment imposed by the Human Lander Challenge. Although the combustion of the exposed working fluid is not a worry due to the lack of Oxygen in space, it is still a possibility for the molecules of the fluid to be bonded to the matter present on the lunar surface because of the extreme heat present in the rockets' exhaust. Because a noble gas is inert, it is the least likely candidate to bond under extreme temperatures to matter present on the lunar surface. The unfurling process is driven by the kinetic energy of the pad being dropped onto the lunar surface. A plunger will be below the reservoir on the bottom of the pad. The pad will land on this, forcing the plunger into the central reservoir and compressing the working fluid, forcing it into the actuators positioned along the outer rim of the pad. The pad will completely and autonomously unfurl itself with the use of this impact energy, while dampening the impact as a whole.

For a 60 ft pad, this comes out to a stowed size of approximately 16.7 ft tall and wide. With a selected material of carbon fiber, the estimated weight of the pad portion of the device is approximately 29,418 lbs (this excludes actuators). When folded, the pad occupies less than 3700 cubic feet of space, allowing the device to comfortably store on its own rocket similar to the Perseverance Rover that was deployed on Mars. This number could potentially even be expanded given payload capacities of modern rockets.

Adherence To Design Constraints & Guidelines

Design measures have been taken to ensure that the landing pad is capable of surviving the harshest of conditions present on the surface of the moon. The main construction of the pad is carbon fiber, and this alone does not have the capacity to resist extremely high temperatures present during the landing phase and potentially sweltering temperatures of the moon's surface. This is due to the restrictions present in the resin that contains the carbon weave. To combat this, in addition to the roughness of the regolith, the carbon fiber panels will have a layer of thermally protective ceramic much like the tiles of the space shuttle. The tiles used on the Shuttle were able to withstand the prolonged, extreme temperatures and the various aerodynamic forces present in its re-entry into Earth's atmosphere.

The hinges will be made of a flexible, yet strong, material to allow for the folding of the pad. A typical hinge would leave room for dust to jam it or let dust through openings so a flexible material for the whole length was selected. The material chosen for this function is Kevlar, as it proved capable of withstanding the extreme cold temperatures present during cryogenic testing (~ -320 F) while still maintaining its strength properties. Kevlar was also chosen due to its great tensile properties.

No assumption of pre-existing surface assets was made, as initially the concept involved dropping the landing pad directly from the Starship HLS during the vertical descent stage of the landing. The intention is that it would be so readily deployable that it could be done with nothing more than the potential energy granted to it by the ship it would be attached to. The implication here is also that the pad is light enough and compact enough to be taken on the Starship HLS. This would mean that the number of required landings would be nonexistent besides the landing of the main craft itself. Following the submission of this proposed concept, it was suggested that this method of transportation may not be viable due to the uncertainties surrounding the unfinished state of the Starship and its intended cargo. Because of this, some design and transportation aspects were adjusted.

Before the Starship HLS lands, an initial mission would be required to deliver the landing pad to the lunar surface. Without the constraints imposed by the Starship's cargo bay dimensions, much larger variants of the pad compared to the original design can be adopted (i.e. larger than 60 ft diameter). Being the only relevant cargo on a separate rocket enables this expansion in scale as well. The size ultimately relies on which vehicle would be chosen to send the cargo to the moon. The allowance of a larger pad would inherently make aiming to land on it much easier. A rocket would also have to ride to the moon with the pad in order to lower it down to the surface and drop it. Depending on mission setup, this delivery system may require a capacity for fuel sufficient to descend from lunar orbit and hover to drop the pad and land itself after exiting the mission area.

Based on this new deployment philosophy, there should be no room for there to be extra risk posed to the crew. In the initial deployment concept, there was the possibility that if the system did not open correctly, there would be a large object in the immediate vicinity that could pose a threat to the lander. A large object that is obscured by the PSI that would now occur due a lack of a protective barrier would most definitely add risk to the landing. The new method of sending a separate landing vehicle prior to the landing of the Starship means that if there are any issues with getting the landing zone ready for the HLS, it will be known well before the landing and can be accounted for through moving the landing zone or other means.

No toxic chemicals are necessary for this pad and the nature of how it works would not expose astronauts to any chemicals as they would be suited up and protected from the vacuum of space and anything that would be on the pad, even if there were harmful materials present.

The landing pad system is purely mechanical, low in part count, and utilizes mature technologies in each of its various components. Pneumatic systems are commonplace in countless machines across numerous use cases and are a well-established mechanism, no matter the size required. Composite materials, namely carbon fiber, are becoming more commonplace in many design contexts and are used in many high-performance vehicles and even in many of the structural components of spacecraft. The structural capabilities of carbon fiber relative to its weight were recognized decades ago and reliable manufacturing methods have been developed since then. This is to say that its creation is a mature technology that will only get better and less expensive with time. Ceramic coating is common in the consumer market for physical and thermal protective use cases. Beyond this, ceramics are a common material to use as an ablative layer for atmospheric re-entry conditions, such as the tiles affixed to the current iterations of the Starship.

Each individual concept and technology required to construct the pad already exists and is well understood. This means that more time and resources can go into the improvement and testing of the pad geometry and structure itself. There are additionally no advanced control or communication systems on the pad itself that would require rigorous reliability testing and radiation hardening. There may be incremental improvements to the folding capabilities through the refinement of the pads geometry and there may be weight savings in areas that bear less loading, but the majority of hurdles that would exist for new technologies are not present for this concept, allowing it to be developed, tested, and deployed in a short period of time.

Changes Made Since Initial Proposal, Work Conducted in Trades, Concept, & Mission Constructs

The main functionality and capabilities of the landing pad itself have remained mostly unchanged from the specifications in the initial proposal. The primary difference between then and now is the method in which the device reaches the lunar surface. After receiving advice on the first submission, it was made clear that storing and deploying the device from the HLS would not be feasible. From there, it was decided that the use of a separate rocket would be necessary, which could lend itself to being beneficial in the area of increasing the size of the pad if the area of coverage was found to be inadequate. An increased area would mean that the Landing Module would have to be less precise when making its descent onto the lunar surface while still being protected from the impingement of the regolith below. Even if the pad were to be scaled up beyond the currently specified 60 ft diameter, the mechanism itself would remain unchanged and would work in the exact same way.

This concept was derived after considering the feasibility of other potential impingement mitigation techniques. The logistics of the chosen method were pitted against the idea to bring the pad system along during the construction of the NASA Gateway Space Station and deploy it from there. Uncertainties surrounding the construction of the Gateway alongside the issues with adding the pad as an additional payload allowed for the benefits of using a separate rocket to shine through and ultimately become what was selected. The mass to trans-lunar injection capability of existing rockets, such as the SLS, surpasses what has been deemed necessary to transport the landing pad and any associated landing/deployment rocket to the moon. By the time the Lunar Starship is functional, it can be assumed that the standard cargo variant of the Starship will be operational. This may be a better option as it is reusable, unlike the SLS, thus saving an exuberant amount of money. The cargo bay would also be able to be dedicated solely to the landing pad and its delivery system instead of the initial concept to include the pad with all the other mission equipment that would be brought along for Artemis III.

Innovative Approaches, Capabilities, or Technologies

The idea of a lunar landing pad itself is already a known technology that will be implemented within the Artemis missions. These landing pads will be constructed once the lunar lander arrives on the moon and will create a solution to future problems with plume surface interaction. These landing pads do not mitigate the effects of PSI on the HLS system as it descends to the lunar surface. The proposed design would allow for a safe and secure landing on an unprepared surface such as the lunar environment. In comparison to the planned lunar landing pads, the proposed solution offers a lighter, less expensive and transportable alternative that will protect the HLS and its crew upon the first landing into a new environment.

Linear actuators enable many innovative applications in space exploration. For example, in-situ resource utilization (ISRU) systems, which extract and process materials from celestial bodies, rely on actuators for operations such as drilling, sample collection, and material handling. These applications are essential for establishing sustainable human presence on the Moon, Mars, and beyond. Actuators in the HuLC Smash system, in this way, are indicative of significant innovation. Actuators within the mechanism allow for precise, controlled, and efficient movements of the various segments that make up the device and allow for the mechanism's deployment to be void of any human intervention.

A second profound innovation found in the HuLC Smash team's solution is the use of origami as a means to transport the mechanism to the moon and deploy it onto the moon's surface in a much larger configuration than what it was transported in. The origami configuration in question takes inspiration from the NASA Starshade, which has been used to shield space telescopes from direct sunlight, leading to clearer photographs to be taken of our solar system and beyond.

Supporting Engineering Analysis & Assumption Justification

Finite element analysis and physical testing with the use of an Instron machine were utilized in the design and engineering of the landing pad. Multiple analyses were performed using finite element analysis in order to find the combination of mesh size, constraints, and force distributions that yielded the best and most realistic results. One simulation shows that with the ground simulated underneath the pad and the weight of the lander on top, under the moon's gravity and distributed onto four landing legs, each having a six-foot diameter, the deformation of the landing pad is 0.027 feet downward. The values plugged into this calculation were from publicly available information surrounding the weight of the Starship. Figure 1 shows a full size carbon fiber landing pad under the aforementioned conditions.

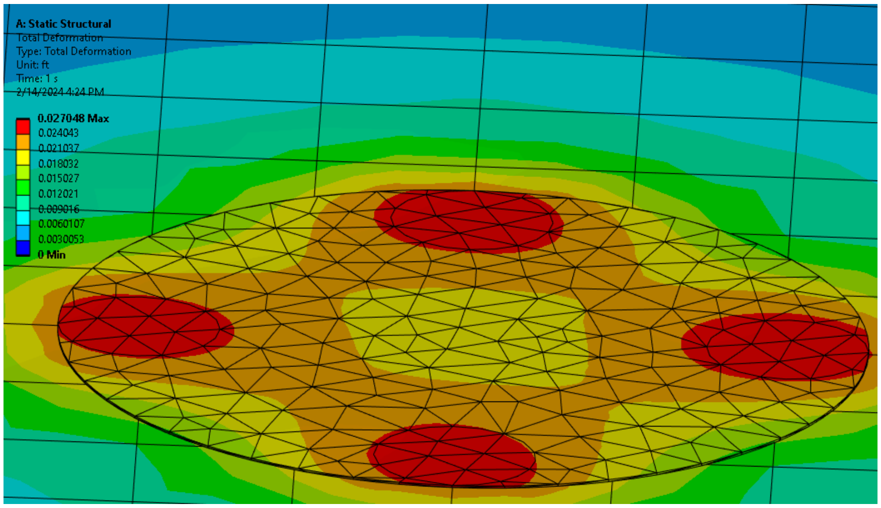

Figure 1: FEA analysis of the landing pad on the lunar surface.

Doing this analysis allowed the optimization of the thickness required to support the lander. This deformation value indicates that the ground provides ample support for the pad, allowing it to be thin and lightweight without reaching yield, or in the case of carbon fiber composites, ultimate stress values. A critical design choice was the thickness of the pad. This determines many other factors, from weight, compressibility, required actuator force, and more. The minimal deformation and subsequent stress was a valuable tool for ensuring the pad was a feasible solution.

Tensile testing of multiple flexible materials was necessary to determine the optimal material for use in the flexible region of the landing pad. The specific tensile properties that were being pursued were the ultimate tensile stresses at extremely low temperatures. The materials selected were chosen due to having particularly high tensile strength at room temperature while also having some component of heat tolerance. The selected materials were a flexible carbon fiber fabric, Kevlar, and Nomex. All materials were soaked in liquid nitrogen for approximately one minute and promptly placed in the clamps of an *Instron* tensile tester. The results are shown in Figure 2.

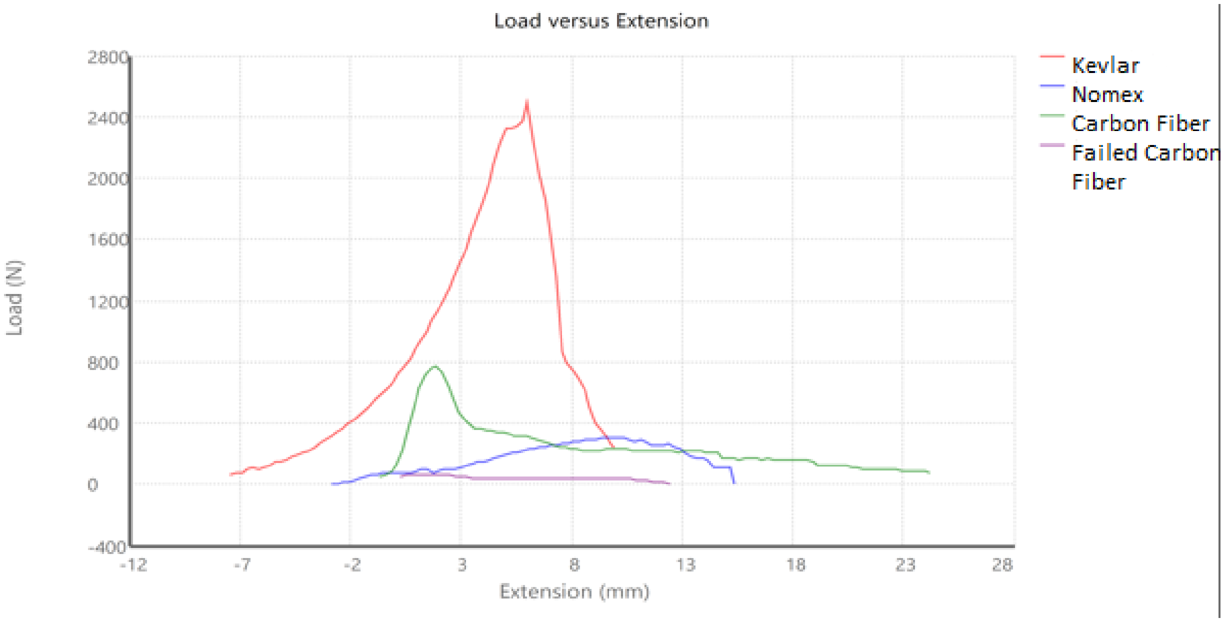

Figure 2: Combined Cryogenic Material Testing Results

As shown in Figure 2, three materials were tested for cryogenic tensile properties. A fourth test was included in this figure to demonstrate the tensile properties of a material should the material have had defects. In each test, a sample strip was submerged in liquid nitrogen to simulate the subzero temperatures of the lunar surface should no light from the sun be shining on it. Seen below in Table 1 are the dimensions and performance of each strip used in the materials testing.

Table 1: Cryogenic Material Testing Results

Material	Cross-sectional Area (mm^2)	Peak Tensile Stress (MPa)
Kevlar	43.2	62.6
Nomex	16.3	19.5
Carbon Fiber Cloth	12.1	42.2

Results revealed that the Kevlar was the strongest material in terms of subzero tensile strength, exhibiting an ultimate strength of 62.6 MPA, about 50% stronger than the 42.2 MPa exhibited by the carbon fiber (second strongest ultimate tensile strength). Furthermore, a simple pliability test was performed on each sample to test each fabric's elastic performance under the same conditions. The Kevlar, alongside each other sample, proved fully effective given their subzero temperatures. Having proven the most effective in terms of tensile strength while also maintaining desirable elasticity/pliability, Kevlar proved to be the best material to use for the hinge.

The value of uncovering the behavior of the chosen materials under the coldest temperatures is in verifying that they will still function in the most extreme conditions on the moon. Making sure that the pad will remain functional once reaching the surface and waiting on the lander is critical to the success of the system. If the material used in hinging became compromised in low temperatures, there would be no use in sending it as the Lunar south pole can get to extremely low temperatures.

The height of the center reservoir was calculated to be 2.213 ft. Using this height, the impact force was able to be calculated. This force was found to be 4.303 MN when accounting for the moon's gravitational constant. The induced pressure on the inside of the reservoir was found to be 117.9 MPa. Based on the mass estimate from the FEA analysis of 13,300 kg, it was found that each actuator would need to displace 2,216.67 kg.

Verification & Validation of Solution

The HuLC Smash team had made use of various computer-aided analysis tools to help make certain the viability of the designed pad. Properties used in these simulations included various material properties pertinent to the competition scope, including but not limited to the lunar regolith at the moon's average ambient temperature, the landing pad at both the Earths and the moon's average ambient temperature, the landing pad subjected to conditions within the rocket plume, etc.

Testing was performed on the Luna-F.O.L.D Mechanism prototype to determine that the device performed its intended function, that being the mitigation of psi. The testing that was conducted used baking flower as a substitute for lunar regolith and a leaf blower to act as the lunar lander exhaust. Testing revealed that the landing pad was able to mitigate almost all regloth from being affected. It was also shown that without the use of the landing pad system, all of the regolith was displaced.

As for system performance, the HuLC Smash team has conducted prototypical testing on a fully-functioning scale model constructed as a capstone project. The prototype was in a folded state with the central reservoir expanded to its maximum, with air being used as the working fluid on this prototype. The “plunger” protruded from the bottom of the central panel of the pad. The pad was then depressed, causing the plunger to retract and force the air out of the central reservoir and into the actuators on the outer edge of the pad through a system of tubing. This forced the panels of the pad away from each other a significant enough distance to fully push the pad open. Based on this scale model, it can be assumed that with the time, money, manpower, and access to advanced manufacturing capabilities, NASA would be capable of taking this functional proof of concept and converting each component into the full-scale, mission-capable version.

Figure 3: Prototype central reservoir and associated tubing.

Figure 4: Prototype in its packed configuration. The diameter of this is just over 7 inches.

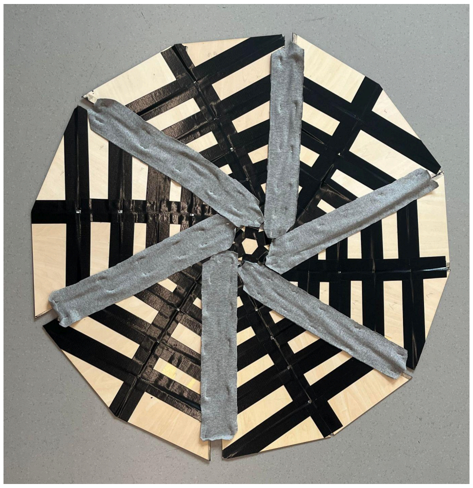

Figure 5: Prototype in its fully unraveled configuration. The gray is elastic material to allow for freer motion at the edges of the pad. This is approximately 36 inches wide.

Conclusions & Key Findings Supporting Approach:

In any mission carried out by NASA, prioritizing astronaut safety is paramount. As the Human Lander Challenge professed, implementing a system to mitigate the potential damage caused by high-velocity ejecta on the Lunar Landing Module is crucial for ensuring their safety. The HuLC Smash landing pad mechanism drew inspiration from pre-existing technologies to effectively manage this issue and ensure minimal barriers to adoption. An origami subsystem was chosen by the HuLC Smash team to be the optimal method for the stowing and the eventual deployment of such a system. In researching pre-existing origami technologies used in industry, the HuLC Smash team discovered the NASA Starshade, specifically its Inner Disk Subsystem [1]. The already- proven NASA Starshade geometry was used as a building block for the rest of the pad. Centrally- located linear actuators, driven by the compression of the working fluid within the central reservoir and its ensuing expansion into the connected linear actuators, would push against the pad's folded panels, driving the unfurling process. Control over the unfurling process was key. Pneumatics has been proven in industry to be a safe and reliable means for driving mechanical motion in a controlled manner. Designing a mechanism that was purely mechanical, void of any electrical components, reduced the overall complexity of the device, helping to further minimize the barriers to adoption for NASA.

There is value in the fully mechanical approach to the landing pad's deployment method. As stated previously, all the components that the pad is composed of are technologically simpler and would be both inexpensive and relatively easy to implement into a full-scale, functioning system. The readiness of the origami technology is apparent in the multitude of published papers on the subject and the research of origami and compliant mechanisms done by groups such as BYU's *Compliant Mechanism Research Group (CMR)*. Their findings have been utilized in many papers and in practical, real-world applications, with one being a collapsible ballistic barrier for use with law enforcement.

This landing pad concept lends itself to affordability. Other proposed methods of developing some sort of landing pad system are expensive and would require large amounts of research and development, such as constructing and sending construction robots and building materials to the moon. Injecting particulate into the Landers engines would require modifications to the engines, leading changes in their mass, movement capabilities, and could potentially require lengthy and stringent testing to approve an engine that has previously been approved in an unmodified state. The origami landing pad is purely mechanical, has a low part count relative to other solutions, and relies on well established engineering concepts and mechanisms. This concept would be more affordable than modifying rocket engines or sending, powering, and controlling a fleet of rovers and making sure they can withstand the harsh lunar conditions. In the simplest of terms, the folding landing pad is a large solid plate of material with a system of powerful linear actuators that deploys under its own power. The majority of the cost would come from utilizing materials that would resist the temperatures of rocket exhaust for the duration of the landing. Little cost would have to go towards a complex control system and a communication network.

Implementation of this concept would require streamlined manufacturing set ups and test stands in order to experiment until a satisfactory design is achieved. In addition to this, a separate rocket would be required to implement the use of this landing pad on the moon. The development of the landing pad would be alongside the development of the Artemis III systems so that it would be complete by the time the HLS is ready. The relatively low cost of the pad paired with its low complexity allows the implementation to be rapid and low difficulty. Because the pad will be carried by a separate rocket, there will be no interference with the payloads or development of the primary aspects of the Artemis III.

Given that the landing pad will be transported before the manned ship arrives, there should be very little risk involved with using this design. By being at the landing site before the HLS, it can be known if there is a malfunction with the system before landing, allowing for a solution to be developed. In terms of utilizing the pad, the risks associated with regolith ejection are minimized and potentially completely negated if the pad covers the entire area that the plume impinges on. Obstruction of landing sensors and visuals of the ground would be prevented. Upon exiting the lander, the pad can act as a staging area to unload equipment onto level, solid ground instead of loose regolith. This also allows astronauts a dust-free zone to remove the particulate off of their suits so it does not get carried into living quarters, preventing the health effects of regolith exposure. There are many facets to the safety/ risk prevention that the landing pad provides, especially in a place as hostile as the lunar surface.

Realistic Assessment of Milestones, Schedule, Operating Costs:

Schedule

The value of this concept is highly apparent for aiming to achieve implementation within 3-5 years. The system's simplicity means that, as aforementioned, it can accelerate through technology readiness levels and be worthy for lunar testing and use before Artemis IV takes place (2028). The way the landing pad is transported lends itself to being low impact on the other aspects of the lander meaning minimal adjustments would have to be made to the systems that are affected.

With the geometry of the envisioned design being as simple as it is, the development of the pad could be streamlined and produced rather quickly. The following is an example of what the project timeline could look like.

Year 1: Manufacture landing pad components, create setup to enable pad assembly, assemble landing pad
Year 2: Test landing pad (properly reduces ejecta, unfurling assessments, test landings with small rocket)
Year 3: Revise design and manufacture the revision
Year 4: Repeat testing
Year 5: Implement into an Artemis mission

With this assessment, the proposed landing pad could be fully implemented into the Artemis program within the next 5 years. The proposed schedule is also likely to be fairly conservative given some of the simple design facets of the landing pad. Some of these facets include the segment design of the pad being able to be machined/laser cut/water cut in large sheets containing most, if not all, of the solid pad pieces, adding to the speed at which the pad could be produced. Likely, the Kevlar binding could be cut out from larger fabric rolls all at once as the envisioned geometry required is of simple geometric proportion and is repetitive throughout the design of the pad. Although it is likely that a setup to assemble the landing pad would also need to be designed and manufactured, this setup would likely not take very long to implement given that similar methods of assembly/testing were also done for the Starshade design. The revision process in year 3 could look much the same so long as the original design is relatively intact.

For years 2 and 4, a full year is a tighter assessment of time. The time and costs associated with just moving the pad mechanism could be substantial as the testing rig could take a month or so just to assemble, the rocket testing could take multiple months to coordinate and carry out, and the cumulative repairs that may need to be made after each deployment could all add up to taking as long as a full year to complete. Both years do possess the potential to take longer than the projected year, but the lead given by the two years of manufacturing and assembly, this outcome is likely not an issue.

Operating Costs

In terms of costs, there are three categories: the initial costs (costs associated with manufacturing/assembling the pad, the cost of manpower needed, any additional constructed setups needed for assembly), the testing costs (costs associated with testing as well as the revision stage of developing the landing pad), and mission costs (costs needed to send the final design to the moon on an actual Artemis mission).

Methods for creating the components to this structure already exist. A methodology similar to that used to create the monolithic wing for the X-32A would be used in the creation of this pad with the benefits of an even simpler geometry and reduced size. Based on material prices and using one of the techniques listed under the NASA costing tools, the carbon fiber material cost would be estimated to be around \$1.3 million. Ceramic heat shielding tiling, much like what was used on the Shuttle of the Starship, costs approximately \$10,000 per square foot [2], which would leave heat shielding the inner 20 foot diameter area of the pad costing approximately \$3 million in total. Braided Kevlar reinforced PTFE tubing, a material known for its high melting point, chemical inertness, and low friction, has been chosen to be used to connect the central reservoir to the linear actuators. Estimates for the cost of this tubing range anywhere between \$200 per foot to \$500 per foot. The HuLC Smash team decided it best to use the average of these costs (\$350) for the device. It is estimated that the device would need approximately 200 feet of this tubing, giving a total cost of tubing to be ~ \$70,000. In total, about 40 feet^2 of 1 inch thick Ti-6Al-4V (Titanium 6-4) is needed to create the central pressure vessel/reservoir. This specific variant of titanium alloy is commonly used for creating aerospace pressure vessels due to its excellent strength-to-weight ratio, corrosion resistance, and ability to withstand extreme conditions. Titanium 6-4 costs roughly \$2,000 per ft^2, with the total for the entire vessel coming out to be approximately \$80,000. In an effort to simplify design considerations related to thermal expansion and other mechanical properties, the same high strength Titanium 6-4 material was selected to be used for the plunger as well. An additional 3.14 ft^3 of Titanium 6-4 is needed for the plunger and is estimated to cost an additional \$85,000. Finally, the actuators would need to be 80 inches long and expand to 132.5 inches. A 54 inch stroke length double acting cylinder costs \$600 dollars each [3]. 6 of these come out to \$3,600. For required insulation and quality checks, or using these cylinders as a baseline against space rated cylinders, an estimate of

$10,000 is made. This leaves a total of approximately $4,550,000 per pad. It is worth noting that this cost is relatively low when compared to the vast majority of NASA vehicles and equipment. Other necessary facets of the build process, like labor and the cost to transport and house the mechanism, cannot be budgeted by the team.

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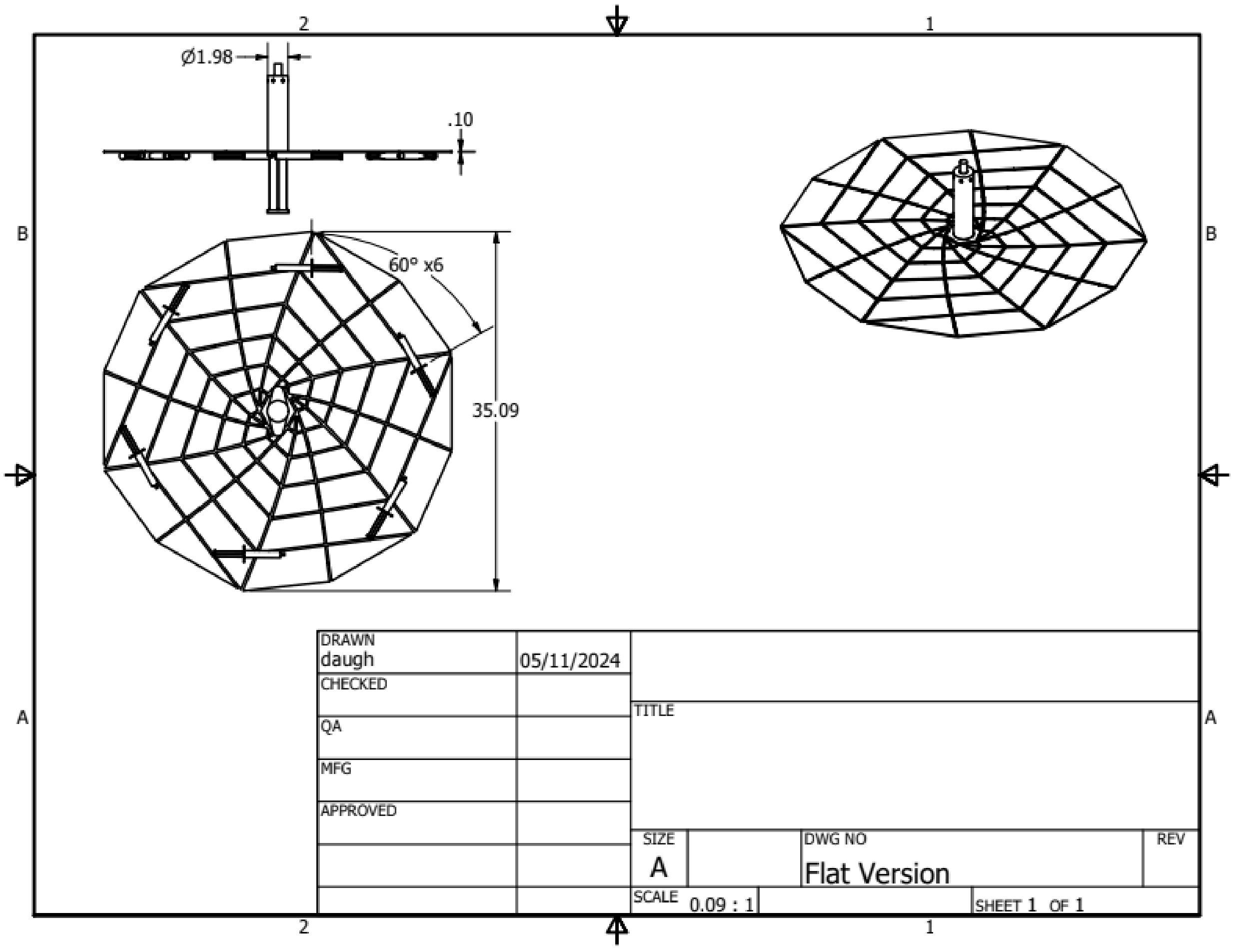
[3] “Double Acting Hydraulic Cylinders | Hydraulic Cylinders | Hydraulics | www.surpluscenter.com,” *www.surpluscenter.com*. https://www.surpluscenter.com/Hydraulics/Hydraulic-Cylinders/Double-Acting-Hydraulic-Cylinders/?page_no=3&fq=price: (accessed Jun. 06, 2024).

Appendix A: Prototype Drawing



Shown here is the dimensioned drawing for the 1/20th scale prototype that was constructed. It can be seen where the actuators bridge and by extension, the panels that are forced away from each other. The actuators, in this configuration, are required to hinge about both ends to allow proper movement. The pad indeed represents a dodecagon and also has room in the center for the central reservoir, whose size is exaggerated in the prototype to account for leaks and other manufacturing inaccuracies.