Team Joint Discovery

Bending Rig for an Electrodynamic Lunar Dust Shielding System

Final Report

ME 4723 – Interdisciplinary Capstone

Dr. Julie Linsey

julie.linsey@me.gatech.edu

Georgia Institute of Technology

Atlanta, GA

Drew Peljovich – ME

Jackson Buley – ME

Sasha Callaway – ECE

Spencer Hopkins – ME

Vikas Muralidharan – MSE

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Executive Summary

Lunar dust poses one of the greatest engineering challenges for sustained human presence on the Moon. Its abrasive, electrostatically charged particles adhere to nearly every surface, degrading materials and shortening the lifespan of critical systems. To address this, Team Joint Discovery was tasked with designing a compact, vacuum-compatible rig to test the bending performance of a flexible Electrodynamic Dust Shield (EDS) thin-film, a promising technology for dust mitigation in future lunar missions.

The design problem centers on creating a repeatable, reliable bending mechanism that operates within the strict constraints of Georgia Tech's high-vacuum chamber. Key technical hurdles include the chamber's limited size (6.1-inch sphere with a 1×1 inch mounting platform) and the need for materials that can withstand 10^{-8} torr without outgassing. The team's solution leverages one existing and one purchased linear bellows drive to cyclically bend the EDS film.

The team created structured design tools including a House of Quality, specification sheets, function trees, morph charts, and evaluation matrices to guide the final product. The team translated stakeholder needs into measurable engineering requirements. Market research and interviews with GT CLEVER researchers and space technology experts further shaped the design, ensuring alignment with both research goals and broader commercialization potential.

The rig's key performance specifications include compact integration within the chamber, repeatable bending cycles, and the ability to activate EDS during testing. Proof of concept was demonstrated by successful cyclic bending of the EDS film in atmospheric conditions. This capability not only validates the EDS under mechanical stress but also supports its potential use in protecting spacecraft components, habitats, and instruments in lunar environments.

The final design is outlined in engineering drawings. Next steps for the project before implementation under high vacuum is to translate these drawings and prototypes made of PLA material into machined aluminum stock. Additionally, a motorized linear actuator will need to be purchased that is ultra-high vacuum compatible to perform the bending test itself.

Nomenclature

Symbol	Meaning
Hz	Frequency, measured in Hertz
V	Voltage, measure in volts
Torr	Pressure, measured in torr

Glossary

Acronym	Meaning
ASA	American Standards Association
ASTM	American Society for Testing and Materials
EDS	Electro-Dynamic Shielding
EVA	Extravehicular Activity
HOQ	House of Quality
IEC	International Electrotechnical Commission
JD	Joint Discovery

Introduction

Team Joint Discovery has been tasked with developing a testing rig to repeatably bend a flexible Electrodynamic Dust Shielding (EDS) thin film in a vacuum chamber. The film is made of a polyethylene substrate with graphene-oxide channels etched into the substrate to form a conductive electrical grid. When an alternating current (AC) of low frequency (10 Hz) and high voltage (>600 V) is applied to the ends of the electrode, the EDS system is "active", which repels dust from its surface. A visualization is shown below in figure 1. Typical EDS devices include conducting electrode thin-films (Indium-Tin Oxide, silver nanowires, etc). The application of these thin films is to attach surfaces that will face performance issues due to dust collections such as solar panels and thermal radiators. Due to the material composition of this specific EDS, it can bend and fold around surfaces as opposed to traditional inflexible designs. This makes it particularly useful for a variety of lunar applications. Possible applications of this system include shielding retractable/extendable spacecraft components, rovers, astronaut spacesuits from excessive lunar dust, and on the outside of inflatable lunar habitats to protect from lunar dust kicked up by human activity nearby.

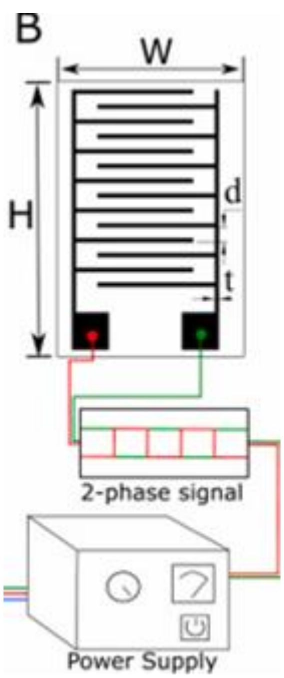


Figure 1: Visualization of EDS device

A testing rig for the EDS system must comply with a set of strict problem constraints for use in a high vacuum chamber. For one, the vacuum chamber reaches pressures of 10^{-8} torr. As such, any equipment inside the chamber must be able to withstand the pressure without collapsing in the high vacuum environment. Additionally, some plastic materials cannot be used in the chamber due to the off-gassing effects that could negatively affect the efficiency of the closed system. Moreover, the vacuum chamber has limited mechanical passthrough and electrical connection availability. The laboratory currently has one linear bellows drive available for use in the vacuum chamber, and due to the high cost of such devices it is preferrable to use the in-stock device without purchasing other systems. There are six electrical connections available, but under operating conditions with the dust dropper functioning and the EDS powered, there are only two connections available.

Most importantly, the dimensions of the vacuum chamber present physical constraints that will significantly impact the design of any internal mechanisms. The central sphere of the chamber measures 6.1 inches in diameter. Within the central sphere sits a lunar dust hopper mounted to the top of the chamber (see Figure 1). For mounting purposes, there is a 1inch-by-1inch platform to secure the bending rig that will attach to the bottom of the chamber. The testing rig that will be used with the EDS will have to conform to these size constraints, potentially sacrificing the ability to perform different types of bending tests with one system.

The desired solution is a compact, vacuum-compatible bending rig capable of repeatable cyclic loading of the EDS film. Key performance aspects include precise control of bending angle, durability under vacuum, and integration with the dust hopper system. Proof of concept will be demonstrated by operating the rig in the chamber with the EDS powered and dust applied, validating dust-repelling performance under mechanical stress.

Value Statements

Scientific Impact: The proposed testing rig will enable scientists to repeatedly test the Electro-Dynamic Shielding (EDS) system under realistic bending and dusting conditions, supporting validation of its dust-repelling capabilities under cyclic loading.

Engineering Impact: The testing rig proposed also improves materials engineering testing in vacuum conditions, forming design improvements and material selection for space-grade components.

Mission Reliability: Supports development of dust mitigation technologies for lunar rovers, astronaut suits, and inflatable habitats, reducing downtime and maintenance in harsh lunar environments.

Commercialization Potential: Facilitates proof-of-concept demonstrations that can accelerate technology readiness levels (TRLs), attract funding, and support patent filings for novel dust mitigation systems.

This report covers Team JD’s initial problem brainstorming, including an analysis of existing products (testing standards, patents), analysis of codes and standards, talking with stakeholders to identify their needs, and the team’s initial designs.

Existing Products and Prior Art

This section analyzes the current state of the art in lunar dust mitigation, with a focus on Electrodynamic Dust Shield (EDS) technology. It identifies the gap in the market for a validated, flexible EDS system and situates the test fixture and experiment plan within this landscape.

Several other dust mitigation strategies have been proposed or tested, but all have significant drawbacks compared to the EDS. (Gaier, 2007)

Table 1: Existing Lunar Dust Mitigation Strategies/Solutions

Solution	Lunar Dust Mitigation Method	Pros	Cons
Mechanical Wiper/Brush	Physically sweeps dust off a surface	Simple mechanical design, potentially more deterministic	Moving parts than can fail due to presence of lunar dust; movement requires additional mass, power, complexity; ineffective for complex geometries
Compressed Gas Jets	Blows dust via a burst of gas	Simple solution with few moving parts	Consumable resource that is mass intensive; can further contaminate environment with dust redistribution
Passive Coatings	Superhydrophobic or other low-adhesive surfaces to reduce dust attraction	Solid state and simple solution	Not active; can wear down overtime with excessive use; cannot remove accumulated dust

The listed non-EDS solutions establish the clear need for a flexible, solid state, low power, and non-consumable active cleaning system. This leads to the currently available and existing designs for EDS systems for lunar dust mitigation.

Patent Search and Related Concepts

A preliminary patent search reveals significant activity in EDS technology, held by Boeing and Boston University.

a. US12121910B2: "Dust mitigation system utilizing conductive fibers" (Boeing Co.). This patent describes a flexible fabric like a dust mitigation system. This specific patent does not describe bending evaluation/performance. It also is focused on using it as a woven fabric which is different from the solution proposed by the GT CLEVER team.

b. US9433336B2: “Self-cleaning solar panels and concentrators with transparent electrodynamic screens” (Boston University). This solution is for a firm EDS used to protect solar panels while still allowing them to harness the sun’s radiation for power. The physical principle of dust removal remains the same as GT CLEVER’s EDS, but it is not flexible.

The existence of these patents confirms the commercial and scientific value of flexible EDS. This project does not seek to invent the flexible EDS itself, but to create the critical bending test required to mature this technology.

A further example of prior art that was found comes from IPC Test Method 2.4.3, which depicts a test set up that is designed to measure the bending performance of flexible printed circuit boards (Technical Committees of IPC, 2022). This prior art demonstrates a proven methodology for testing the mechanical durability of flexible, conductive materials, providing a foundational reference for the EDS-specific test design.

Relevance and Differentiation for Intended Design

The test fixture and bending experiments are relevant to the prior art as stated before but is still distinct to be its own project. The focus of this project is to quantify the EDS’ bending as a commercial selling point. The test fixture will generate the quantitative data (e.g., "cleaning efficiency remains >95% after 1,000 bend cycles to a 5mm radius") required to substantiate this advantage to potential customers like NASA. There exists no commercial "Flexible EDS Bending Test Fixtures" on the market. The design addresses a specific, unmet need within the R&D pipeline for this emerging technology.

Existing Testing Systems

There are very few existing test systems that allow cyclic bending of a flexible film inside a vacuum chamber, particularly in laboratory-scale vacuum systems. Most vacuum test fixtures focus on thermal cycling, outgassing characterization, or static mechanical loading, not repeated flexing of thin-film electronics. Because of this, the closest prior art comes from adjacent domains that required similar mechanical-in-vacuum capabilities.

One of the most relevant examples is a NASA study titled “The Effect of Vacuum on the Fatigue and Stress-Rupture Properties of S-816 and Inconel 550 at 1500°F.” (Freche, 1965). Although the study investigated high-temperature fatigue in metallic specimens rather than polymeric films, the mechanical test architecture is directly applicable to the requirements of a flexible EDS evaluation.

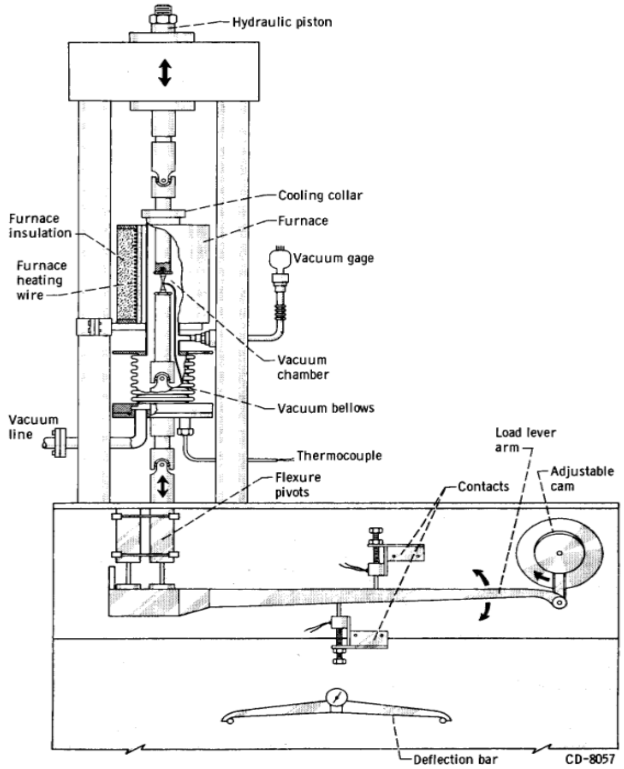


Figure 2: Fatigue Test Apparatus

Although the mechanical scale and material system differ from the thin-film EDS, this NASA apparatus demonstrates that cyclic bending in vacuum can be achieved using external actuation and vacuum-mechanical interfaces. The NASA fatigue apparatus serves as architectural precedent but fails to provide the specific integration of vacuum operation, controlled bending radius, and electrical excitation needed for flexible EDS validation.

Codes and Standards

Several codes and standards informed the ideation of the first prototype. Included in this section is a summary of those codes and their relative importance.

IEC 62899-202-5

IEC standard 62899-202-5 is the most applicable to team JD's final product. An excerpt from the introduction highlights the basis for the reason behind this application:

> *In this document, a mechanical bending test is described to evaluate the electrical property of a printed conductive layer on a substrate under repeated mechanical deformations. This sliding plate test method can be available for practical application in the industry by enabling the long-term reliability testing of printed film. (TC 119 - Printed Electronics, 2018)*

The EDS system is very similar to the film described in the standard. A graphene layer is printed on top of a polymer substrate to repel the lunar dust. Furthermore, it is necessary to repeatedly deform the piece to understand its resilience to bending. The standard gives clear instructions on how to perform the test, and the structure of the bending rig itself. When comparing team JD's ideation to Figure 3, the IEC standard served as a clear inspiration for the final design.

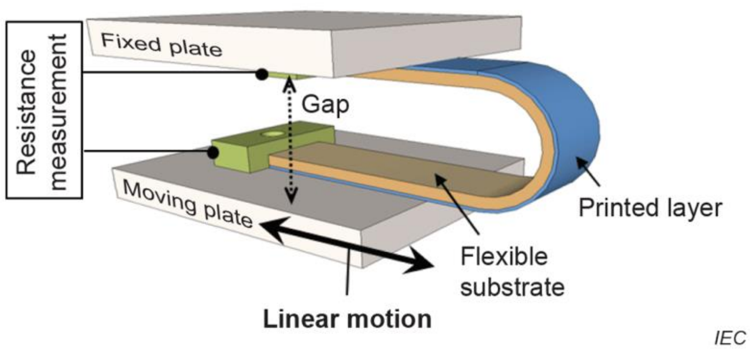


Figure 3: Schematic diagram of mechanical test of printed film

While not explicitly described, the standard does call out for variable adjustment of the gap between fixed and moving plates. Team JD will implement this variability in the final design, but not follow the exact mechanisms described in the standard. The test depicts the horizontal motion of the printed layer by the moving plate. After speaking with key stakeholders, this will not be possible in the final design. Therefore, Team JD will have to modify the standard so that it can perform in a vertical position.

Other Applicable Standards

During the ideation phase of the project, Team Joint Discovery found and used several other standards as a basis for the final project. While not implemented as directly as 62899-202-5, these standards guided the team towards the end goal and provided inspiration for certain design choices.

Figure 4: ASTM F392 Torsional Test

The first of the standards considered was ASTM F392, called *Standard Practice for Conditioning Flexible Barrier Materials for Flex Durability*. This standard describes a torsional test of flexible packaging material used in food packaging and shipping. Originally, Team JD considered the possibility of a torsional rotation test performed in the vacuum chamber. This standard was extremely useful to help ideate this application and described the specifics of conducting such a test. The benefit of this standard over others was the mechanics of torsion helped simulate a new variety of loading conditions for EDS. Torsional tests better simulate end uses of EDS such as twisting limbs on a spacesuit. However, after consulting key stakeholders and understanding of the project, the spacesuit end case of EDS was determined to be less feasible than the other uses of EDS. As such, this standard was not directly adhered to in favor of other testing methods.

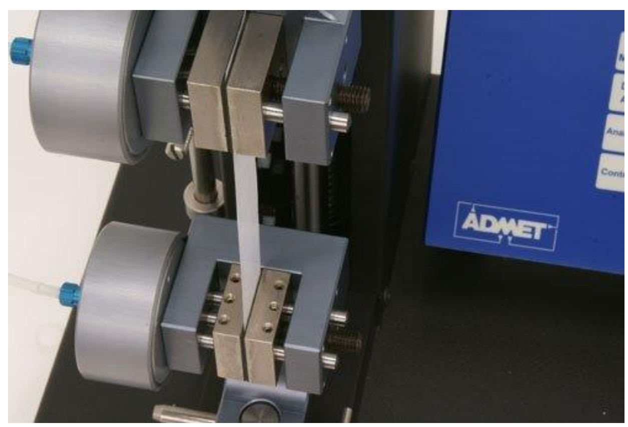


Figure 5: ASTM D882 Tension Test

Additionally, another type of testing not pursued by team Joint Discovery was detailed in ASTM D882 titled: Standard Test Method for Tensile Properties of Thin Plastic Sheeting. This standard outlines the procedure for conducting a single plane tensile test. The purpose is to measure the film's modulus of elasticity and compare the stiffness to theoretical results. This test would have simulated an extendible spacecraft part or other actuating equipment. However, conducting a tension test in the vacuum chamber with preexisting linear actuators is a trivial task. While the overall test was not selected to govern the final design, Team JD did take inspiration from the clamping mechanism for the test. One of the challenges in the final design of the overall system was how to clamp the EDS to the mounting plate. Using inspiration from this test on the clamping mechanism for the EDS was very valuable in the final design in understanding how to hold a thin plastic film.

Furthermore, two standards related to flexible devices were investigated. First ASTM F1683: *Standard test method for folding endurance of flexible organic light-emitting diode (OLED) devices.* The beauty of this test is that its purpose is to roll and bend a film over and over again. The standard offers a fairly simple test to study bending, but the team did notice that a large amount of material would be needed to effectively test the EDS.

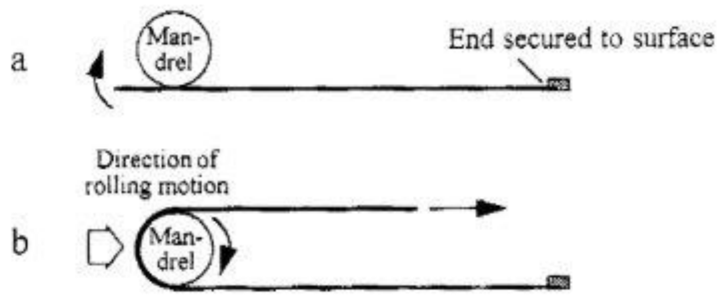


Figure 6: ASTM F1683 Visualization

A result of the small sample size meant that this standard could not be faithfully used, but the simplicity in design was something the team carried forward. Lastly, the time also investigated IPC-TM-650: *Testing method for repeated bending of flexible printed circuit boards.* The motivation to look into this standard was that it closely resembled the EDS device: a flexible printed film. The team dubbed this test a "piston test" as there was a rotating CAM that enabled the repeated bending of a test specimen. In this device, there is a standard spacing between ends of the flexible PCB design, which the team thought was limitation for the EDS.

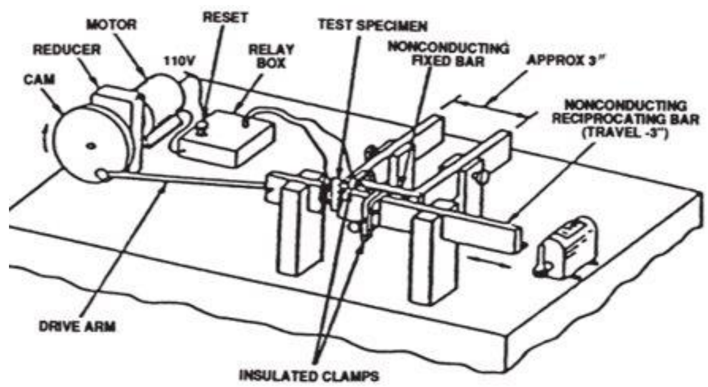


Figure 7: IPC-TM-650

The positive idea of this standard is the ability to impart motion from a distance from the sample. This idea was taken as inspiration during the concept generation and prototyping phase.

Ultra-High Vacuum Standards

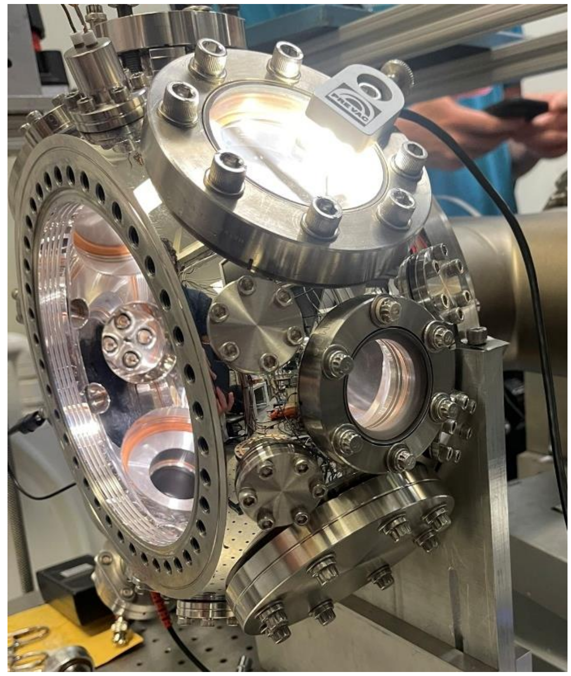


Figure 8: Side view of Vacuum Chamber with ASA Standard Flanges

Any mechanical part in use in the ultra-high vacuum chamber must be specifically designed for the extremely low-pressure environment. This includes complying with the standardized American Standards Association (ASA) flanges and fittings. These allow for mechanical and electrical passthroughs to be fed directly into the chamber during use and create a leak-tight seal preventing failure. The testing rig that is being designed must comply with these standard flanges. As seen in later designs, the use of a linear actuator is paramount to the final design's success. This linear actuator is a vacuum standard part and complies with the ASA flanges. Any additional parts will also have to be standard and purchased from a verified vendor that supplies these types of parts, such as the Kurt J. Lesker company.

Furthermore, any part in use inside the vacuum chamber must be designated vacuum chamber compatible. This is a specific designation that is different than outer space vacuum compatible. These vacuum chamber parts have to be designed to minimize outgassing effects, where small contaminations can ruin the experiment being conducted in the closed chamber environment. To get the designation, only very specific equipment can be used, which could potentially drive up the costs of the final product. The team will have to design the final product very carefully to account for these parts and take note of their associated costs.

Customer Requirements

This section will analyze the customer requirements and how these translate into engineering specifications. Included is a stakeholder chart, list of customer requirements, engineering design specifications, and finally a house of quality.

Stakeholder Analysis

The stakeholders are specific personnel that team Joint Discovery actively engages and collaborated with in pursuit of the project goals. Table 2: Stakeholder Matrix shows all of the stakeholders and their relative importance/influence on the project.

Table 2: Stakeholder Matrix

Stakeholder	Interests	Importance	Influence
Dr. Linsey (sponsor)	Ensure delivery of working prototype and adherence to ME guidelines	High	High
Luca and Ide (Grad Students)	Oversee the project and give vital feedback on our designs. Understand the end goal and can steer us in correct direction.	High	High
Dr. Alvoro Romero-Calva (AE Professor)	Has expertise on the companies and the end-use for the EDS system, can give guidance on proper tests to conduct on the system.	Medium	High
Dr. Orlando	Oversees the lab and the grants given to GT clever to conduct this research. Knowledge of available parts and mechanisms to use.	Medium	Low
NASA	Provides the money to GT clever to develop the EDS testing rig. Financial interest in the project's success.	Medium	Low
Space Companies	The end user of the EDS product, will purchase the system to apply to space missions in the future and will want data quantifying its performance.	Low	Medium
Dr. Meisha Sofner (MSE Professor)	Has expertise on thin films and can give guidance on proper testing procedures and techniques.	Low	Medium

Communication with high importance stakeholders is conducted on a weekly basis at minimum. These are conducted through in person meetings and frequent online messages. This is done to ensure the team stays closely aligned with the project's end goals, with constant collaboration necessary to steer the team to the same direction envisioned by the project sponsor and grad students.

Additionally, while not directly tied to the success of the project, stakeholders such as Dr. Romero-Calva and Dr. Meisha Shofner are great resources to understand the project specifics and gain feedback on certain unknowns during the ideation phase. Finally, NASA and other space companies are interested parties in the product. Since they are interested in using the EDS system on future lunar missions, getting data on efficiency while bending is critical. These stakeholders are less involved in the ideation and prototyping phases of the project, but critical in the product. Their needs and requirements are fed through the other stakeholders and ultimately guide team Joint Discovery's process through the capstone semester.

Customer Requirements and Functionality

While the EDS system works well in a well-controlled environment, the team behind its development has little data on the lunar repulsion in states of bending. **Therefore, the main requirement for the project was the development of a bending rig that could perform bending to the EDS system while in the vacuum chamber.** However, no specific test or degree of bending was required, only that the bending rig should be able to give quantifiable data to researchers to understand how the EDS works.

The EDS system as a whole needs to be marketed as a reliable and dependable system. Without hard data showing its efficiency in different loading conditions, the team at GT clever cannot sell the device for use on the moon. **As such, another overarching requirement is to gain usable and impactful data from the bending rig.** This requirement is also kept vague as to not constrain the types of tests that team JD might want to run. The purpose of this requirement is to remind the team that at the end of the capstone semester; the stakeholders are looking for data to substantiate their claims about the EDS system. There is no measure of "how well" this can be accomplished, only that any data is better than none.

Lastly, because of the vagueness of the problem, there is a need to relate the bending tests to something more standardized. This way, when presenting the results of a bending test to an end user, the data can be related back to a regulated standard to help explain what they mean. **Consequently, the testing rig must be closely alighted with an ASTM or food safety standard.** The specific standard is left vague, again as to not constrain which types of bending tests can be performed. However, alignment with *at least one* standard is paramount so that the system and its results can be understood much easier.

Engineering Design Specifications

This section of the report will discuss the specifications for the engineering design of the final product. Included will be an analysis of the constraints and a specification checklist that will inform a House of Quality that summarizes the overall tolerances and requirements for the project with specific tolerances included.

Engineering Constraints

Despite the open-endedness of the problem, there are still many constraints for the project. First, the system must work inside an ultra-high rated vacuum chamber. This poses a series of connected requirements for the overall design: the physical size of the chamber, material selection, and availability of feedthroughs. Additionally, the chamber uses standard feedthrough windows that any purchased part must be compatible with. The high-rated vacuum also poses specific material constraints. Plastics and other polymers have severe off-gassing properties that could cause damage to the system. As such, only metals and other vacuum-rated parts can be used inside of the chamber during operation.

Engineering Design Specifications

Based on the customer requirements, engineering functionality, and constraints for the project, team Joint Discovery has created a robust set of engineering design specifications that will encompass the project scope. As seen in Table 3: Engineering Design Specifications List, the team has developed 5 main categories of requirements: General, Physical Characteristics, Electrical, Mechanical, and Performance.

Table 3: Engineering Design Specifications List

		Issued: *9/23/2025*		
		For: Team Joint Discovery		
		Specification		
Date	**D/W**	**Requirements**	**Source/Rationale**	**How Validated**
General				
23-Sep	D	Perform bending on the EDS system up to 180 degrees	Perform full bending test of EDS	Observe Final Design
23-Sep	W	Bend the test piece while electronics are powered and lunar dust is dropped on top	Give data to researchers about the functionality of EDS during bending	Observe Final Design

23-Sep	D	Allow for camera view of film during dusting + flexing	necessary for measuring performance of film	Observe Final Design
29-Sep	D	The testing rig is not to obstruct the dust deposition from the shaker	The test specimen must continue to be dusted while bent	Observe Final Design
23-Sep	W	Allow for variable radius of bending	Give data correlating radius of bending versus the effectiveness of EDS	Observe Final Design
Physical Characteristics				
23-Sep	D	Must fit inside the vacuum chamber (<155 mm diameter)	Provided by Luca Scifoni	Measure final design overall size
23-Sep	D	Must be capable of mounting within vacuum chamber	Provided by Luca Scifoni	Observe final design
29-Sep	D	Compatible with 2"x1.5" films for 2-phase configuration	Provided by Ide Onal	Measure final design overall size
29-Sep	W	Compatible with 3"x2" films for 3-phase configuration	Provided by Ide Onal	Measure final design overall size
23-Sep	D	Materials used must be high-vacuum rated (10^-8 torr)	Provided by Luca Scifoni	Select materials that withstand this pressure
Electrical				
29-Sep	D	Use Kapton insulated wire for all harnessing internal to chamber	Provided by Luca Scifoni	Observation
29-Sep	W	Use vacuum rated linear actuators	Provided by Luca Scifoni	Material selection
Mechanical				
23-Sep	W	Limited to use of lab provided linear actuator as mechanical feedthrough	Due to limited funds, not requiring the purchase of additional high-vacuum parts would be beneficial for the final design	Observe final design

1-Oct	W	Build in a heat dissipation method to cool motors during operation	Due to the small enclosed space, heat can rapidly build up in the chamber and affect the operation of internal equipment. Need a way to control the environment temperature during experiment	Heat Transfer Sensors
Performance				
23-Sep	W	Bendable for 1000 cycles before failure	Provided by Ide Onal	Run fatigue life calculations on testing rig to ensure product lifespan
29-Sep	W	Adhere to IEC 62899-202-5 testing standard	Provided by Dr. Orlando, standard selected is most similar to EDS applications	Compare final design to testing standard

The general category describes the overall functionality of the bending rig. Bending the test piece a full 180 degrees while allowing for dust to drop on top of the polymer in view of the camera is a critical functionality of the testing rig. Failure to comply with these requirements would result in unusable equipment for the purposes of the project.

The physical and electrical characteristic requirements describe barriers for the system in real space. They dictate the maximum size allowable in the chamber, compatibility with test pieces, and availability of electrical connections. These physical requirements, while not explicitly related to the end goal, are critically important and stem direction from the problem understanding.

The mechanical and performance categories dictate the practical applications of the bending rig. They explain how the system needs to function and give requirements for the ways that the bending can be induced.

Importance of Specifications (House of Quality)

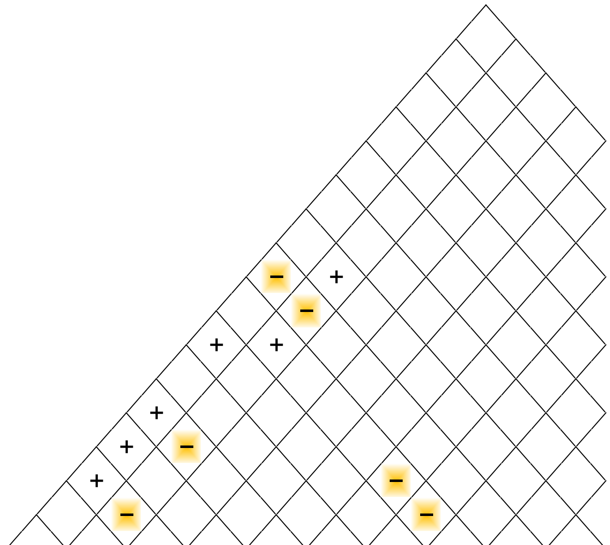
Together, the constraints and requirements can be summarized into a house of quality showcasing the importance of each task. The HOQ lists the customer requirements and engineering requirements, giving the specific tolerances and target values as well.

Project: Joint Discovery
Revision: 1
Date: 9/30/2025

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Category	Weight	Column #	1	2	3	4	5	6	7	8	9	10
		Direction of Improvement	◇	▼	◇	◇	▲	◇	▲	▼	◇	▼
		Customer Requirements (Explicit and Implicit) / Engineering Requirements	Perform Standardized Bending Test on EDS	Size	Bending Test designed for 2 and 3-phase dsigns sizes	High Vacuum Rated Components	Variable Bending Radius	Autonomous Control	Bending Cycles	Power Consumption	Accommodate variable susbtrate thicknes	Subassembly Count
	10	Bend EDS System in Vacuum Chamber	●		●	●	▽		●			
	8	Record Bending Test with Camera and Dust Shaker On	▽	●						○		
	6	Perform test on multiple sizes of substrate	▽	▽	●		▽				●	
	6	Perform test while EDS and vacuum chamber are powered		▽	●	●				●	▽	
	6	Change the radius of bending	○			▽	●					
	5	Limited Oversight Necessary During Testing						●		●		
	7	Use system to calculate fatigue life	○						●			
	4	Minimize Expenses per Test		○	▽	▽		○		●		▽
	9	Minimize Set-up/Dismantle time		○				○				●
		Target	180 degrees	<155 mm diameter	2x1.5" & 3x2" test piece	10^-8 torr	0.1 - 20 mm	Use vacuum rated electrica feedthrouh	1000 cycles	Use (2) vacuum rated feedthrough	1 - 0.1 mm	1 (fully assembled)
		Technical Importance Rating	143	123	202	154	70	84	153	159	60	85
		Column #	1	2	3	4	5	6	7	8	9	10

Figure 9: House of Quality

After gathering the customer requirements from key stakeholders, the most important customer requirement is bending the EDS system in the vacuum chamber. This tracks from the overall goal of the project, and serves as a reminder for the team to stay unified in completing this shared goal. Furthermore, it can be sold off by a variety of engineering requirements and their target values: performing standardized bending test on the EDS (180 degrees), bending designed for 2 and 3 phase sizes (2x1.5" and 3x2"), high-rated vacuum components (10^-8 torr), and number of bending cycles (1000). Designing a testing rig that can accomplish all of these engineering requirements will satisfy the customer's needs and be marked as a successful project.

The second most important requirement was not as obvious to the team at first. That is minimizing the set-up and dismantle time. Direct cost is not a critical requirement in this project (listed with weight 4) as the price to run the vacuum chamber and purchase the materials is low. The true cost is associated with the grad student's salaries and available time to work on the project. Since they have other tasks and work to complete as part of their schooling, minimizing the time needed for them to actively work with the testing rig is a key requirement. This will indirectly drive down the costs of the system and allow for other work on the EDS system to be completed. Set-up time is directly tied to the subassembly count, meaning the team is trying to create a fully assembled testing rig that would minimize the time needed to set up.

Subsequently, recording the bending test with the camera on is the third customer requirement listed for the project. The camera is the only way to quantify the amount of dust being repelled by EDS, and so recording the experiment is paramount for the team. This is strongly tied to the testing rig's overall size and positioning in the chamber. At its diameter, the vacuum chamber measures 155 mm. Additionally, the top area is dominated by the lunar dust dropping mechanism. Available space for the testing rig is tight, and positioning the rig so that it is viewable from the camera will be a challenge. However, failure to accomplish this task will starve the researchers from gaining useful information about the EDS behavior in bending applications.

The other customer requirements, while not weighed as high, are still useful to team JD in understanding the project goal. They are translated into engineering requirements that shape the final product and help focus the capstone team into achieving these goals.

Market Research

This project's market research and potential impact scope can be understood through two different lenses: as a product for GT CLEVER's EDS research team, and another for the EDS as a product for space agencies and commercial organizations. For the former, the focus is providing a solution to the research team to demonstrate and evaluate their EDS's bending performance. For the latter, the market and impact are significantly larger and not as hyper specifically concentrated on a certain client.

Market Research Plan

The market research plan for the GT CLEVER research group will consist of meeting and interviewing people directly involved with the EDS team. The graduate students working on the project will provide Team JD with hands-on knowledge of constraints and customer needs. Specifically, Luca Scifoni is the aerospace engineering PhD student who works directly with the vacuum chambers that the EDS is tested in. The specific mechanical and environmental constraints of the vacuum chamber are central to the problem and the information garnered from talking with Luca will be invaluable. From the material science perspective of the problem, Ide Onal is the material science and engineering PhD student who will provide the necessary information for the evaluation of the EDS's bending characteristics. Dr. Julie Linsey is the resource for general questions regarding the scope and performance of the project.

From the perspective of the EDS as a commercial product for space related organizations, Dr. Romero Calvo, director of Georgia Tech's Low-Gravity Science and Technology Laboratory (LGST Lab), will be the main point of contact for interviews and questions regarding the market and potential impact. Further resources will come from publicly available space organizations for documents and plans. This specifically includes NASA roadmaps and Artemis mission plans.

Market Research Results

The interviews and discussions with Dr. Linsey and the graduate students working with GT CLEVER provided important context for the design of Team JD's product but also insight into the market. The market for the specific device that GT CLEVER would use to evaluate their EDS is constrained to just the GT CLEVER organization. Therefore, it is quite limited in terms of commercial viability. There is a potential to sell this product to other research or commercial organizations who develop their own version of a flexible EDS and would like to test their device to the same standards as the ones done by the GT CLEVER team. If validating GT CLEVER's EDS bending performance using the aforementioned standard and test fixture becomes the industry accepted way to test such shields, it would create a market for commercial and research organizations seeking to buy or license the technology. This market would be significantly smaller than that of flexible EDS as it would likely be a one-off purchase for the company or research organization to validate their design.

From the commercial side of this project, market research is more tangible. The first part of this is understanding where the EDS could potentially be used, as it is not designed for a hyper specific use case now. A significant part of the discussions with Dr. Calvo and research focused on potential applications. These include but are not limited to shielding spacecraft components and actuators, instruments such as cameras, extravehicular activity (EVA) suits, and habitat modules. Dr. Calvo expressed significant doubt of EDS working with EVA suits due to the human factors risk associated with high voltages on the outside of the suits. The other applications, however, leave a lot of room in the market for EDS. This section of the report will briefly focus on the market of EDS from two lenses: mass saved due to EDS protection, and the mass saved due to picking flexible EDS over another lunar dust mitigator. Astrobotic is a lunar services company which provides numbers for soft landings on the lunar surface (Astrobotic Payload Management, 2021). Using their provided value of $1.2 million dollars per kilogram, the EDS can create vast market value just from mass savings alone. It is hard to put specific numbers now due to the early stage of EDS development, but if an EDS can protect or increase the lifespan of just 10kg of sensitive lunar infrastructure (instruments, hatches, actuators, etc), EDS has provided a value of $12 million in just delivery costs, let alone the savings from not having to purchase the replacement infrastructure and the losses caused by its downtime. This calculus can further be used to demonstrate the mass savings by using extremely light weight and low power EDS as opposed to other lunar dust mitigation strategies such as mechanically actuated metal brushes and cold gas thrusters (Tatom, 1967). For full scale Artemis missions, the potential mass savings impact of the lightweight EDS could be on the order of hundreds of millions of dollars. Further, the EDS is a solid-state system, requiring no additional mass to function (such as cold gas thrusters), relatively low power as opposed to mechanically actuated systems, and no moving parts, so reliability is significantly higher.

Market Research Impact on Design

Important context for the design of this project to demonstrate the EDS' bending performance as a commercial selling point. Keeping this in mind, the market research learned has adjusted the specific standards and tests that Team JD will use to demonstrate the EDS' characteristics. Talking with the GT CLEVER researchers who are directly involved with this project has significantly helped tailor the design and strategy for this project, giving specific feedback and information that constrains the problem to create an effective solution. Such specific feedback includes the environmental constraints given by the vacuum chamber and the specific type of wiring and materials that must be used in high vacuum.

Design Concept Ideation

Functions to be Filled by Design

The primary function of the design is to enact repeated stress tests on the EDS subject and analyze the device's performance in repelling artificial regolith after multiple cycles. At the highest level, this can be split into 3 sub-functions: Induce Stress on the Substrate, Mount and endure testing within the chamber, and produce validated and replicable results:

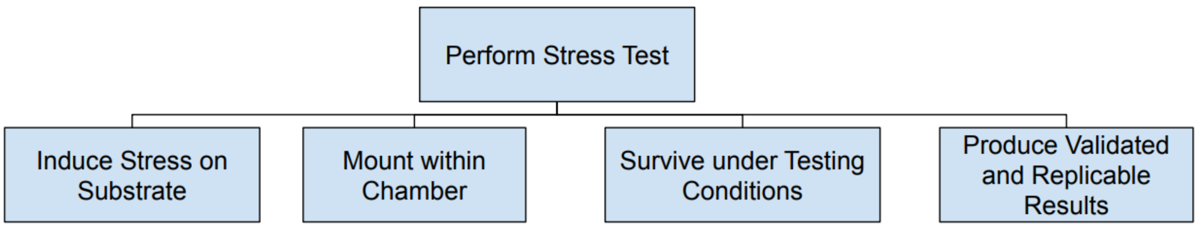


Figure 10: High Level Function Tree

Inducing stress on the EDS device can vary greatly in form depending on the standard adhered to. However, all can be broken down into a mechanism to induce motion on the substrate coupled with a mechanism to resist this motion. Both will be reliant on how the EDS is mounted within the rig as well.

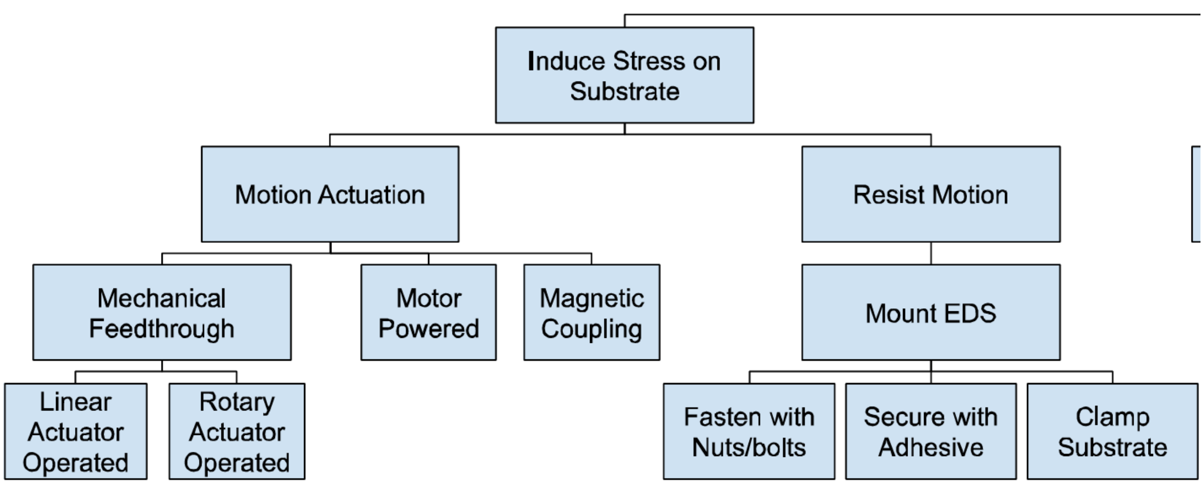


Figure 11: Function Tree Branch 1

To adequately perform stress tests, the design also must be mounted in the chamber while enduring the optimal testing conditions – Vacuum rated conditions, power running through the EDS, and artificial regolith falling. Mounting within the chamber is constrained by the current equipment and the testing environment.

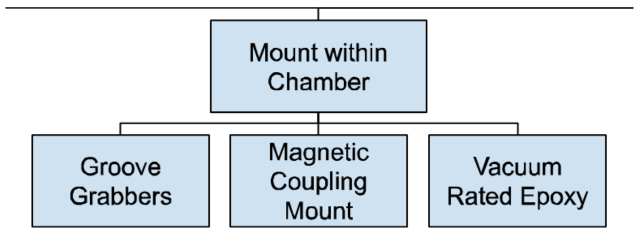


Figure 12: Function Tree Branch 2

To endure this environment, the rig must be vacuum rated and be able to avoid suffering damage from regolith wear. Regolith is a harsh substance which can create multiple failure modes in testing, and thus the rig must be designed with countermeasures in mind. To avoid this damage, parts must either be selected to be strong enough to not be worn down by it, have regolith continuously removed from them, or not move when regolith is present.

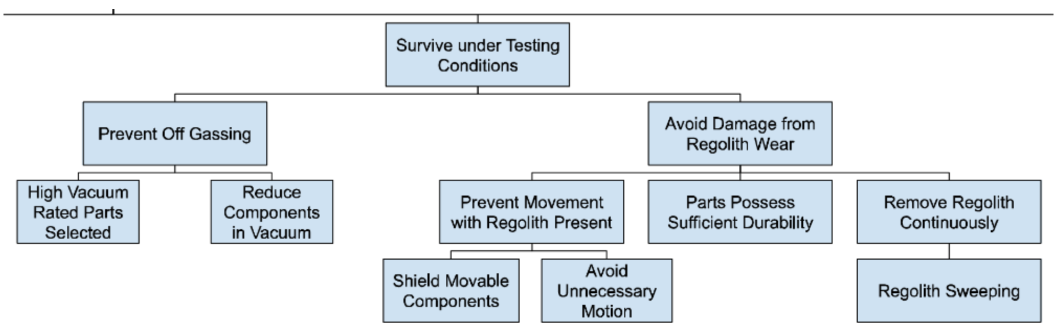


Figure 13: Function Tree Branch 3

Lastly, even if the testing is performed, it is not relevant unless it provides meaningful and replicable results. As such, it must adhere to a relevant testing standard and perform meaningful data collection. To determine meaningful data collection, there also must be established criteria for success or result validation. Team Joint Discovery has devised multiple alternative solutions for these functions that define the testing essentials, and the successful completion of them will provide a strong basis for a working prototype.

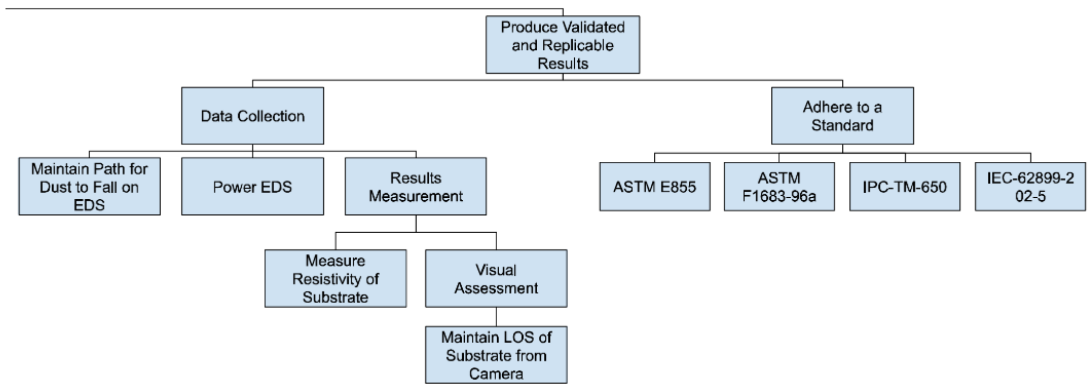


Figure 14: Function Tree Branch Number 4

Alternative Solutions to Fulfill Functions

Inducing stress on the EDS involves a means of moving the substrate while providing resistance. Motion can be provided via mechanical feedthroughs in the form of a linear or rotary actuator. Other options include a magnetic coupling paired inside and outside of the chamber, or utilizing a vacuum rated motor which only requires electrical feedthroughs, which are significantly more available. To resist motion, the EDS can be held stationary by threaded fasteners as have been done in previous non-bending tests, a vacuum rated adhesive, or a clamp to distribute the load.

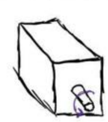
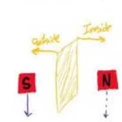
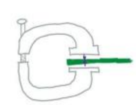
Motion Actuation	Linear Actuator Operated 	Rotary Actuator Operated 	Internal Motor Powered 	Magnetic Coupling 
EDS Mounting	Fasten with Nuts/Bolts 	Secure with Adhesive 	Clamp Substrate 	

Figure 15: Morphological Chart - Motion Actuation and EDS Mounting Mechanisms

The mounting of the rig within the chamber can be done in a few different ways with varying stability, cost, and reliability. One method is with Groove Grabbers, a part made by the manufacturers of the vacuum chamber to be joined at the flanges and mount components inside. Another option is mounting via magnetic coupling, and finally via a vacuum rated epoxy.

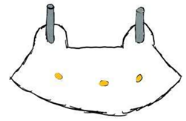
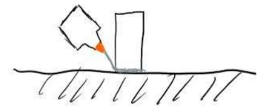
Test Rig Mounting	Groove Grabbers	Magnetic Mounting	Vacuum Rated Epoxy
			

Figure 16: Morphological Chart - Test Rig Mounting Mechanisms

An additional critical aspect of the testing rig is being able to survive under specific testing conditions. Primarily, they must be vacuum rated, have no off gassing, and be able to avoid damage from regolith wear. Considered manners of avoiding regolith wear include selecting parts durable enough to avoid frictional wear, preventing movement of parts near regolith, and removing the regolith continuously before potential points of contact with a sweeping mechanism. Preventing movement of parts near regolith can consist of shielding the movable components or replacing/eliminating motion altogether where it is non-essential.

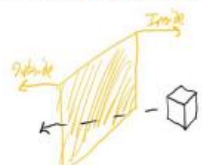
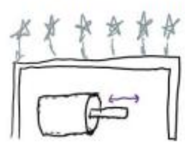
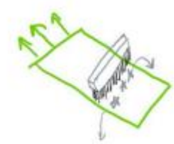
Prevent Off Gassing	High Vacuum Rated Parts Selected 	Reduce Components in Vacuum 	
Avoid Damage from Regolith Wear	Shield Mobile Components 	Possess Sufficient Hardness 	Regolith Sweeping 

Figure 17: Morphological Chart - Mechanisms to Survive Testing Conditions

Finally, it is critical for the stress testing to produce meaningful data in a replicable manner by following a relevant testing standard to provide a level of validity to the results, as well as being able to measure and collect this data consistently. There were a wide range of ASTM and IEC standards examined for various forms of stress testing and applications which are further examined as the basis of our integrated concepts. Important subfunctions of data collection included establishing a method of assessing results and include the current method of visual inspection via a camera and measuring the resistivity of the circuit when stressed as discussed in *ACS Appl. Polym. Mater. 2025, 7, 9211-9223*. Additional essential components of testing involve providing power to the EDS through electrical wiring feedthroughs and dusting the specimen to assess its repelling capabilities. This can be done by either bending the specimen multiple times and then dusting it or dusting it as it is being bent. These solutions address the subfunctions necessary to produce meaningful data that is desired by the end user.

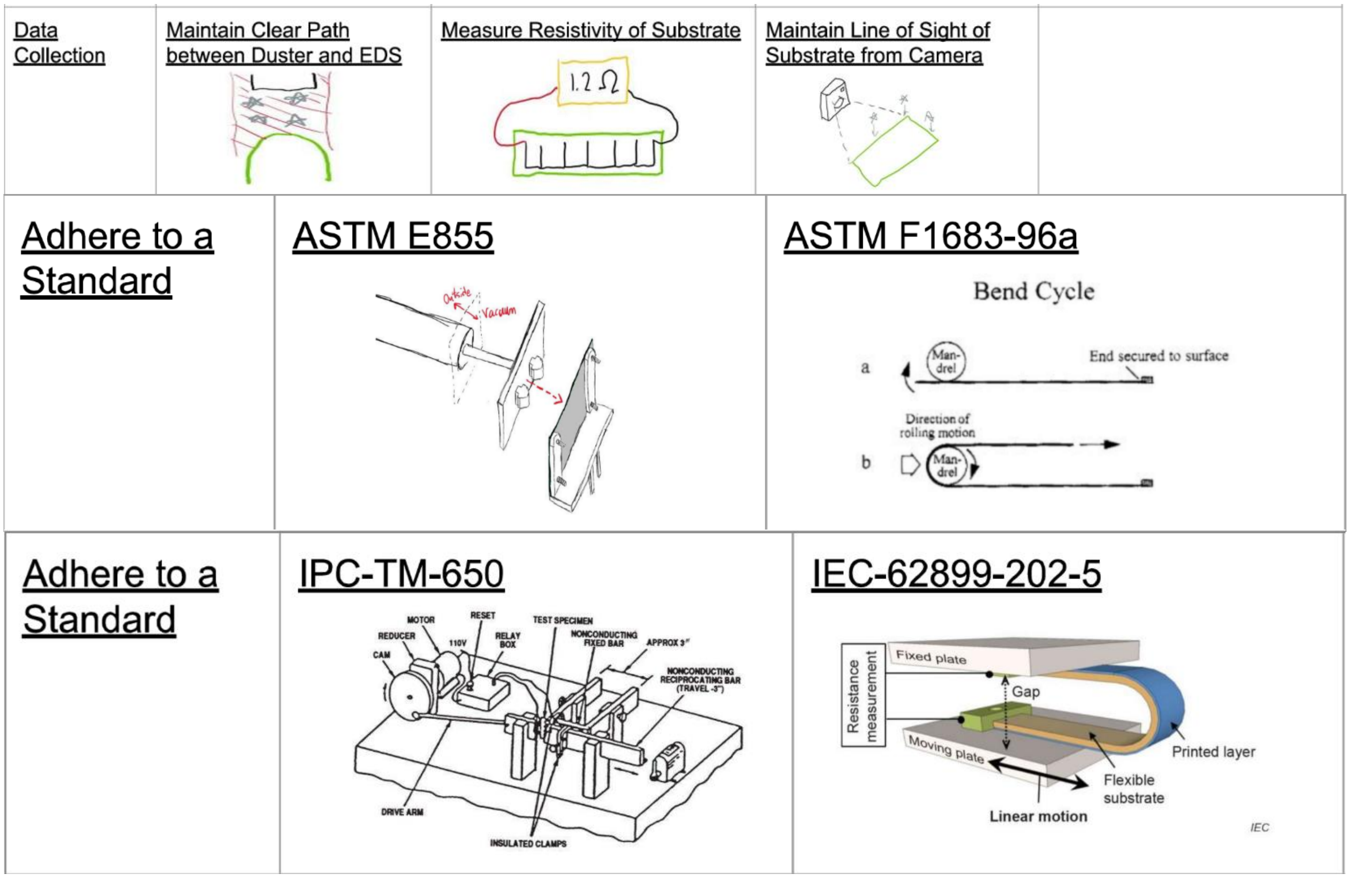


Figure 18: Morphological Chart – Mechanisms to Collect Meaningful Data

Integrated Preliminary Designs

The most influential subfunction for ideation early on was selecting a standard to adhere to. The various standards examined served as our bases for design in our more fleshed out and integrated concepts. These integrated concepts were each centered around a standard while integrating different versions of the previous subfunctions. Bending, tension, and torsion are three ways to quantify the movement of the film, but some applications of this EDS would have a combination of two or three. Therefore, the team also considered more generic tests for fabric folding emulation and a creasing consideration.

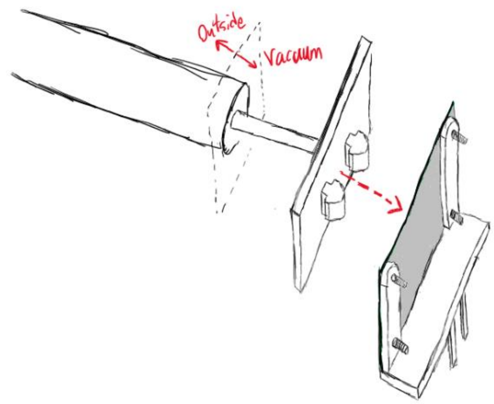


Figure 19: ASTM E855 Based Bending Test

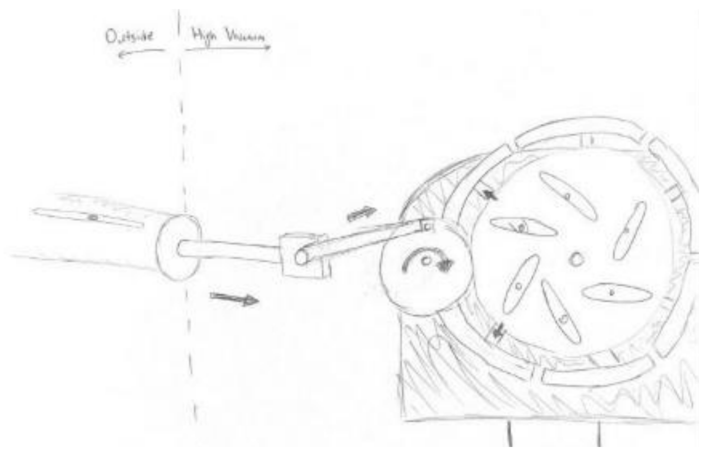


Figure 20: Variable Radius Bending Test

Bending is a very likely mode to be encountered in the EDS' widespread potential applications. It can be found in the movement of joints, both mechanical (on curved surfaces and actuators), or human, (on a spacesuit). Due to this wide range of applications, multiple potential bending tests have been developed with varying degrees of bending, bending radii, and points of contact. One testing method, inspired by ASTM E855, involves a 3 or 4-point bending test where a neutral substrate is prodded in one or two locations to induce bending stress. Another uses a slider-crank mechanism to convert linear motion to rotary, rolling a mandrel (that can be variably sized) across the static test piece to induce bending stress. Another standard that the EDS could potentially be tested to is specified in IPC-2223 and IPC-6013D, which establish standards for the design and qualification/performance of flex and rigid flex PCBs. These standards refer to the IPC-TM-650 Test Methods Manual which specifies fatigue tests and fatigue behavior for flex PCBs. ASTM F1683-96a provides a bending standard that is most obviously applicable to this

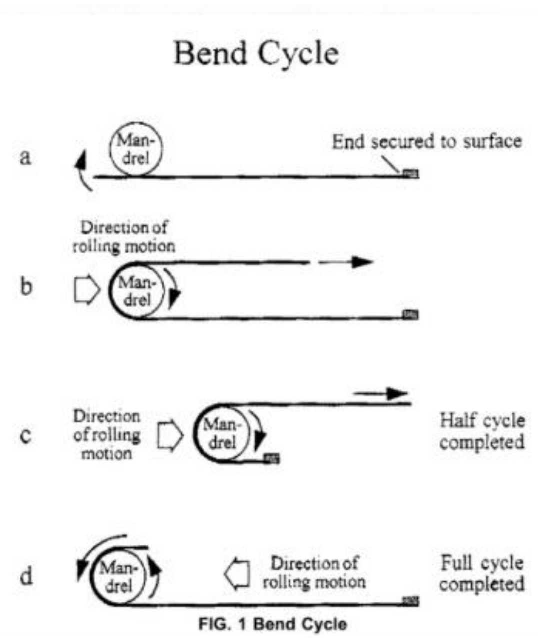


Figure 21: ASTM F1683-96a Bending Test

testing, although it may not provide sufficient understanding of how the device operates under different types of bending.

Tension is another primary flexing mode that could be useful for an application engineer to understand before utilizing this film on their product. For example, if this film were used on an inflatable structure (balloon-like), it would be vital to know how much it can strain before lunar dust mitigation is compromised. Therefore, a linear tension test could provide repeatable information for performance as a function of stress or strain (likely strain, considering the linear actuator which is available). The drawback to this test is it would not consider bending, which could be a very important flexing mode to understand when evaluating the performance of these films.

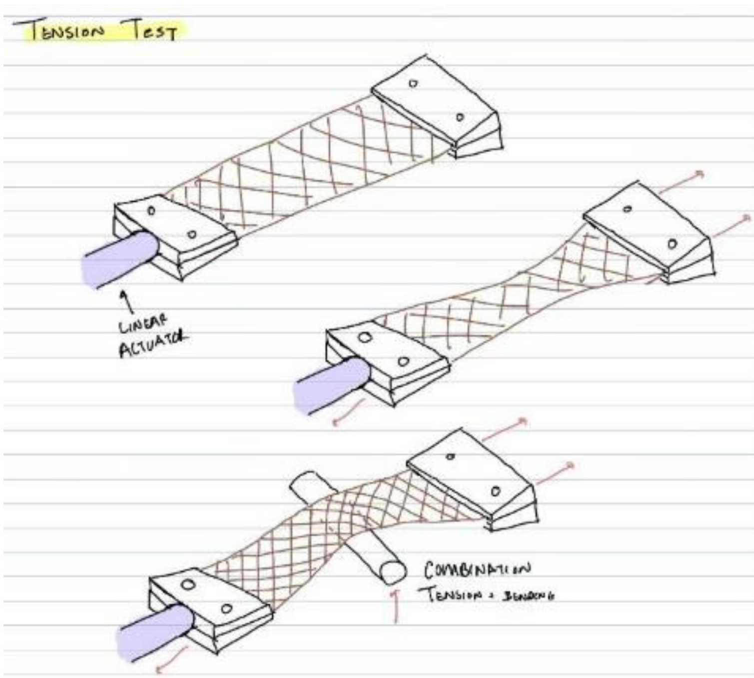


Figure 22: Tensile/Bending Test

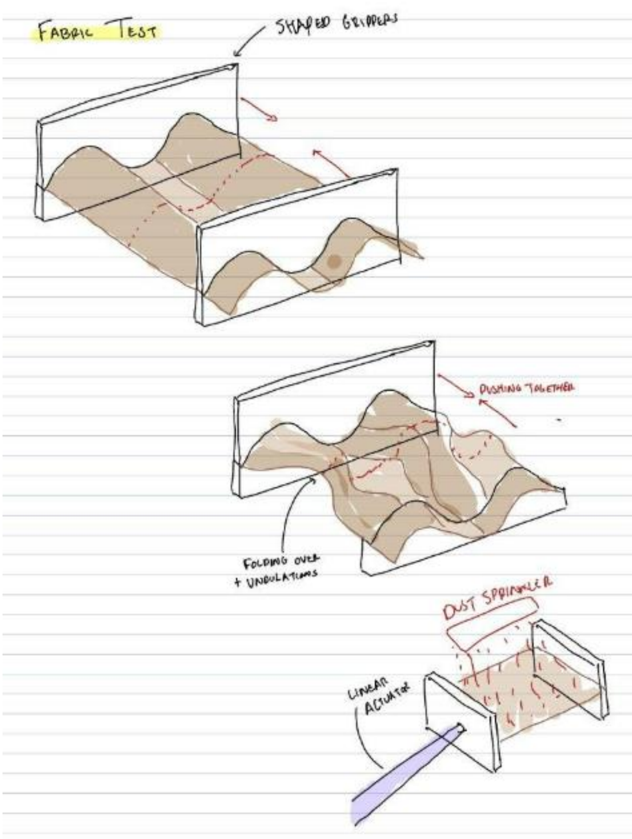


Figure 23: Fabric Replication Test

A general case for these flexible EDS's is with foldable, fabric-like surfaces including space suits and inflatable habitats/satellites. If these are intended uses, a test that demonstrates the ability of the EDS to reject dust while folded or stored akin to these cases would showcase the film's efficiency in these applications. For this reason, the team is proposing a vacuum test that focuses primarily on enforcing fabric-like folding behavior. These tests would be qualitative in nature, as it would be difficult to quantify the number of wrinkles in a fabric. This test also has the advantage of using only the linear actuator, which would simplify the device. However, if the primary goal of this project is to showcase the film's effectiveness under this specific use-case, this demonstration would be the most effective showcase of such. From the team's discussion with Dr. Linsey and Dr. Romero-Calvo, the application of this device to spacesuits seems unlikely, and so this specific use-case does not seem like the most important test to pursue.

Concept Selection and Justification

There is a good understanding of what the system could test, but it is vital to properly define what testing the setup should actually perform. There are many standards that could be tested, and the selection of which design should be pursued is a combination of how well the appropriate standard applies to the desired application and how feasible the device is to fabricate and meet the strict requirements on space and vacuum rating. Going into the concept selection phase, three primary designs were considered, each of which provides a different set of valuable information for how the films act under bending.

Design #1 is designed for the specific standard IEC-62899-202-5, and consists of a linear actuation that repeatedly bends the film, with some sort of secondary adjustment to change the radius of the film. This test meets a standard that very closely applies to the film being tested, and is feasible with the constraints listed.

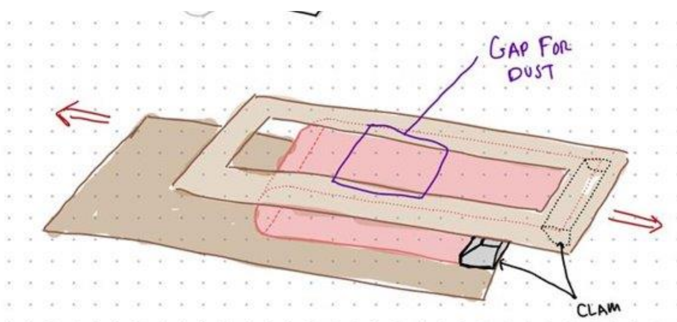


Figure 24: Sketch of Design #1

Design #2 is designed for the standard IPC-TM-650, which is the broader standard for flexible circuit boards. There is some documentation online about a theoretical device used to test this standard, but not any specific drawings or details.

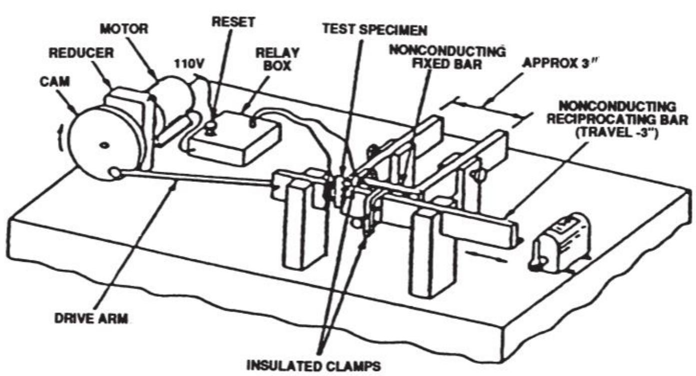


Figure 25: Drawing from standard, Design #2

Option #3 is a design that is not based in any standard, but could provide valuable insight into the film under a larger variety of flexing tests. The tradeoff here is more freedom to test with the drawback of not meeting a strict standard.

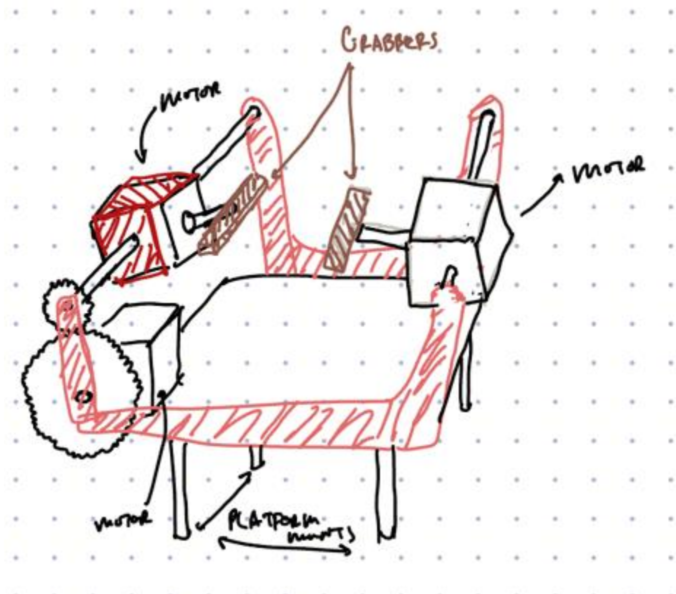


Figure 26: Sketch of Design #3

In order to adaquetly evaluate these designs, an evaluation matrix was made to compare how each idea effectively meets the requirements. The most important criteria were that the film should adhere to a standard, since this will provide the best data for effectively communicating to potential investors the true capabilities of this device. As seen in Figure 21 Design #3 had significant hits in this category. However, as expected, Design #3 shined in criteria that were focused more on versatility. Specifically, #3 scored highest in the testability while being viewed with the camera and unobstructed, since this design has more freedom for how the film is held and mounted.

Design #1 had high potential in most of the other categories, especially with the ability to test with different Radii, and generally scored highly in all of the cateogories. The resulting scores for each design resulted in a selection of design #1.

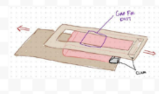
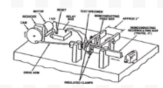
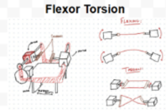
Criteria	Rated Importance	IEC 62899-202-5 		IPC - TM - 650 		Flexor Torsion 	
		Rating	Weighted Total	Rating	Weighted Total	Rating	Weighted Total
Bend EDS System adhering to a standard	9	4	36	4	36	1	9
Test with the camera on (and unobstructed), and dust falling	7	3	21	2	14	4	28
Perform Test on multiple substrate sizes	5	3	15	4	20	4	20
Perform Test while EDS and Vacuum chamber are powered	7	4	28	4	28	4	28

Figure 27: Portion of Evaluation Matrix, highlighting standard adherence

Total		178		165		147
Relative Total (divided by 200)		0.89		0.825		0.735

Figure 28: Results of Evaluation Matrix tally

With Design #1 selected, there are many questions about how the device will operate. The two main functions it must serve are to displace linearly to flex the film and to displace in a perpendicular direction to change the radius. To adjust the height, several options were considered. Most options included using a motor, which left the decisions to be made if a vacuum rated motor should be used inside of the chamber or if a mechanical passthrough would provide higher vacuum capabilities. Figure 23 is an initial sketch of an adjustable height that utilized springs and a string with a spool to adjust the height.

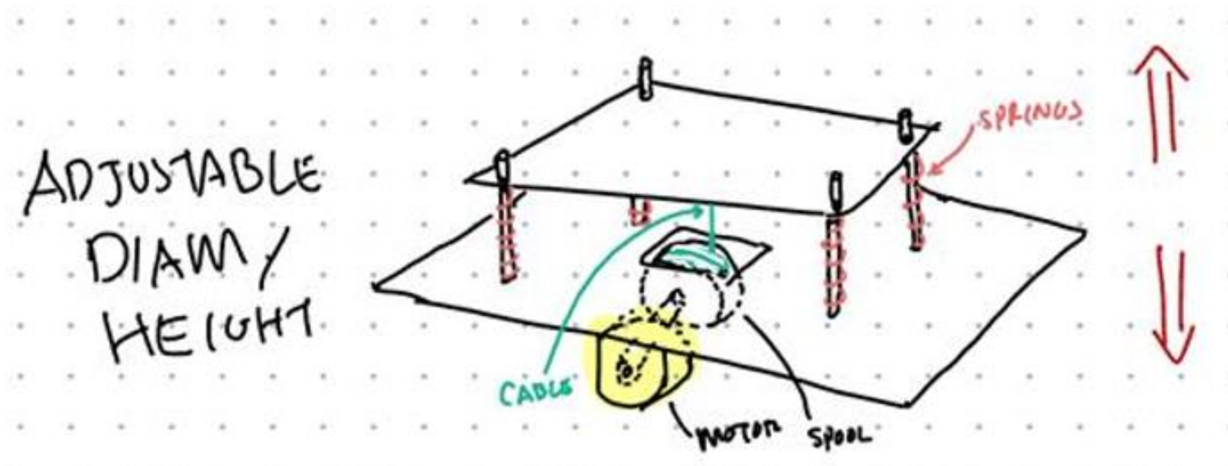


Figure 29: Sketch showing one method for adjusting the height of a platform using a motor

Another option that was considered was to use a lead screw with gears, which would provide precise control over the platform height and be stiffer than the other option. If using lead screws, it would the be necessary to decide between a single screw or multiple. To choose between these options, the main consideration was complexity and resistance to wear from regolith. The spring method seems very complex, and it has added issues of the motor requiring a constant holding torque to resist the spring movement. This could be solved with a one-way torque mechanism, like a worm and worm wheel, but this is extremely complicated and requires expensive hardware that would be prone to wear. Lead screws have the advantage of being self-locking and simple to drive. Using four lead screws would be the most secure option but would likely require many larger gears to split the motor output, which would add mass to the setup that could increase the cantilevering effect. A single lead screw would be smaller and more compact, but sliders would be required to support the platform on a post which could become stuck or wear away over with regolith.

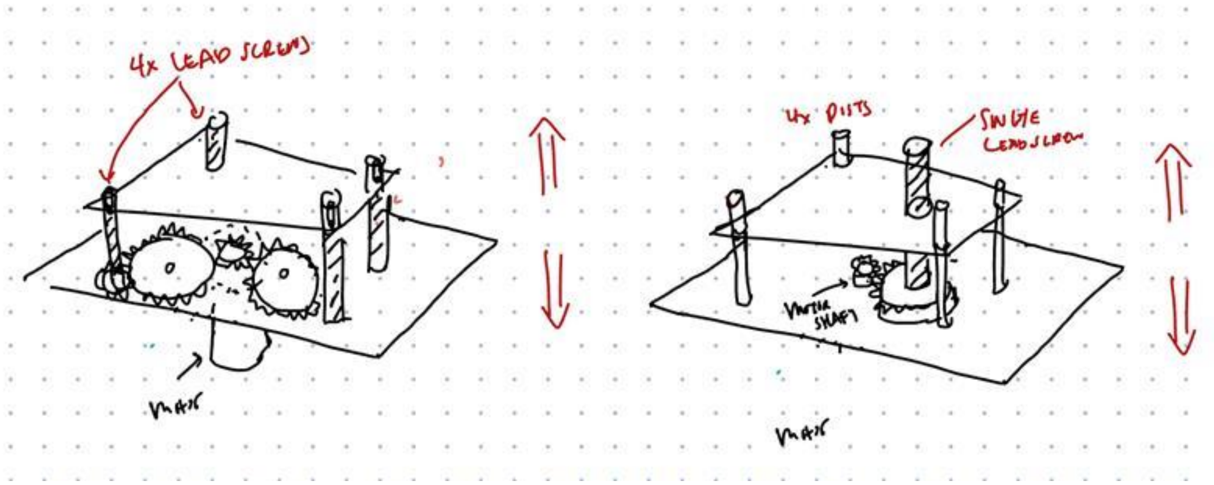


Figure 30: Sketch comparing single lead screw configuration to quad configuration

The current plan is to prototype both options and see if either has issues with the mechanism actuating. By identifying this early in the design process, risk will be eliminated. Another mechanism that required decision making was on the linear actuation. It could be possible to drive this using a motor or using the supplied linear actuator. The supplied linear actuator is the preferred design, since it will mount to the chamber directly and would not require linear slides. Linear slides are a high risk item for regolith to ingress and eat away, and should be avoided. Vacuum and physical space are the two largest considerations when making these decisions, since it is important be able to bring the chamber down to the required vacuum level. This will likely mean some trade-offs have to be made, such as purchasing an extremely expensive motor that is rated for this level of vacuum, or ditching a mechanism for a linear actuator as those are easier to buy off the shelf and meet the vacuum requirements.

Figure 25 shows the current up to date CAD, which utilizes groove grabbers to mount to the vacuum chamber, a lead screw to move the platform, and a linear actuator to move the device. The largest challenge when constructing this CAD model was with packaging; even small components and plates are large in proportion to the vacuum mounting geometry.

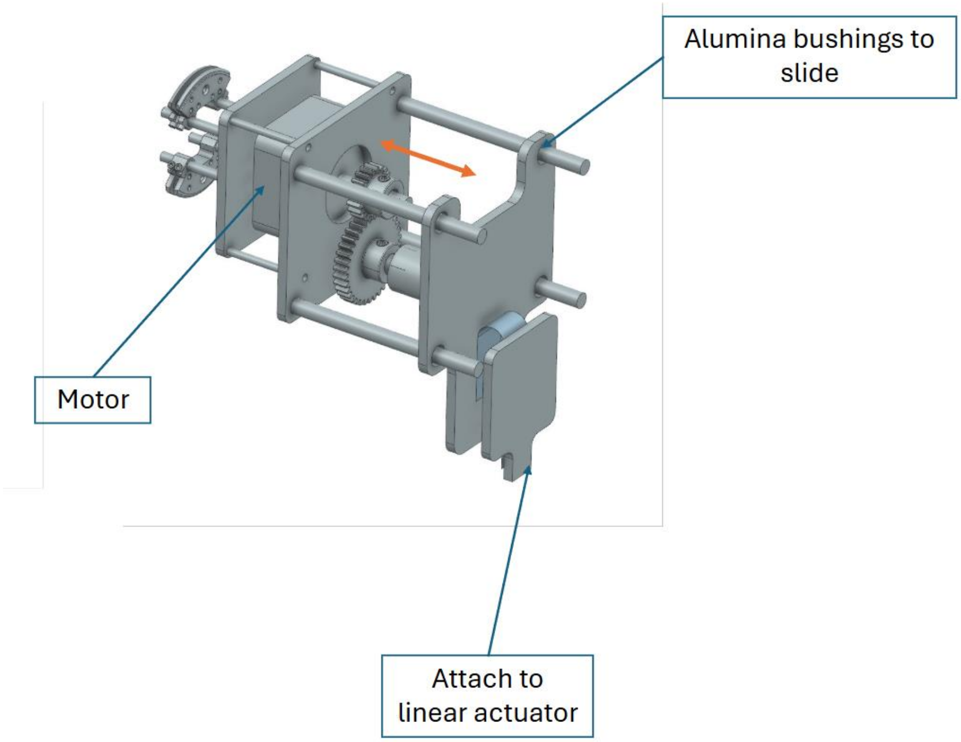


Figure 31: CAD of proposed design

One open risk is with regolith not being repelled by the film and becoming trapped between the film and the platform, as shown in Figure 26. This would cause serious damage, as the regolith is extremely abrasive in nature, and would likely lead to an early failed test. One idea for prevention would be to use a mesh that would allow the dust to fall off of the film instead of being trapped, which could reduce wear.

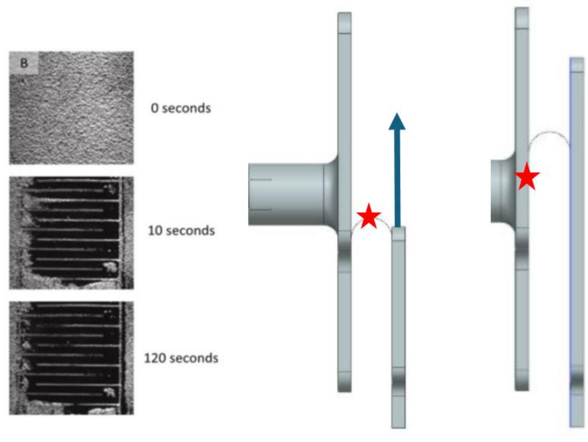


Figure 32: diagram showing how regolith can become stuck between film and plate

Another risk for this design is not being able to properly see the film under actuation. When the stroke is at its full length, the film is visible from the default camera port. However, at the other end of the stroke, the film is completely blocked by the plate. This could be an issue, if it is desired to view the film under the full stroke length. However, it may not be necessary to view the film under the full stroke. In this case, this will not be a concern, but if full view is desired, the camera can be set up to view through the main viewport instead.

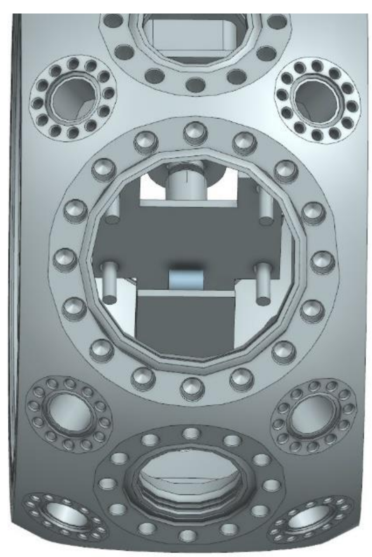


Figure 33: View of film at bottom of stroke length through standard viewport.

Industrial Design

Considering the human factors in the design of the final product is important for any capstone group, including team JD. Even though most of the testing rig will be located inside the high-vacuum chamber and inaccessible to direct human contact, there are still aspects of the design that could be simplified to reduce the cognitive load on the user. Namely, the user interface will have to be designed carefully so that the user understands what they are programming for the controller to perform.

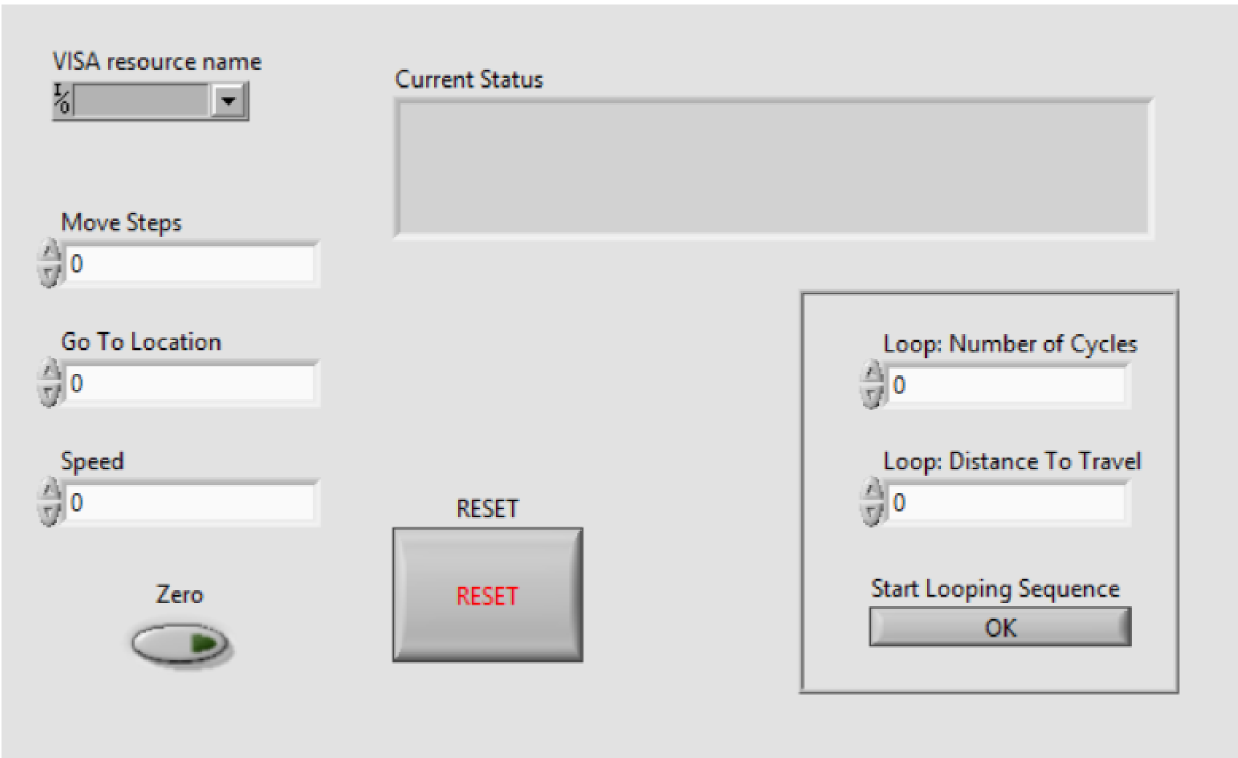


Figure 34*: LabView Interface to Interface with the Motor Controller*

The number of bending cycles, speed, and stroke length are customizable parameters that the user can input via a LabView interface. The *Current Status* tab displays serial output from the controller with helpful information including the actuator's current position, target position, speed, and the current loop cycle its in. The *Zero* button allows for the user to set the minimum/initial position value of the actuator. The design can easily integrate with limit switches which would be mounted externally to the vacuum chamber. This allows for closed loop control, and the motor spins until it hits the end stops of maximum position and minimum position.

Additionally, the horizontal actuation will be performed manually using the non-powered linear actuator. This actuator will determine the bending radius of the EDS during testing. After discussing the project parameters with the key stakeholders, it was important to minimize the number of times that the vacuum chamber had to equalize with atmospheric pressure. Therefore, the bending radius can change without directly affecting the pressure in the chamber. In terms of industrial design, the actuator is very simple to operate and ergonomic. To change the bending radius, all the user must do is twist the end of the actuator. Each full revolution of the dial corresponds to 0.1 mm change in bending radius, allowing for very fine adjustments of EDS. This minimizes the chances of accidentally over/undershooting the desired radius and potentially causing damage to the overall system. Furthermore, to visually aid the user when changing the bending radius, a ruler will be installed inside the vacuum chamber mounted to the EDS mounting plate that can visually instruct the user as to the current bending radius.

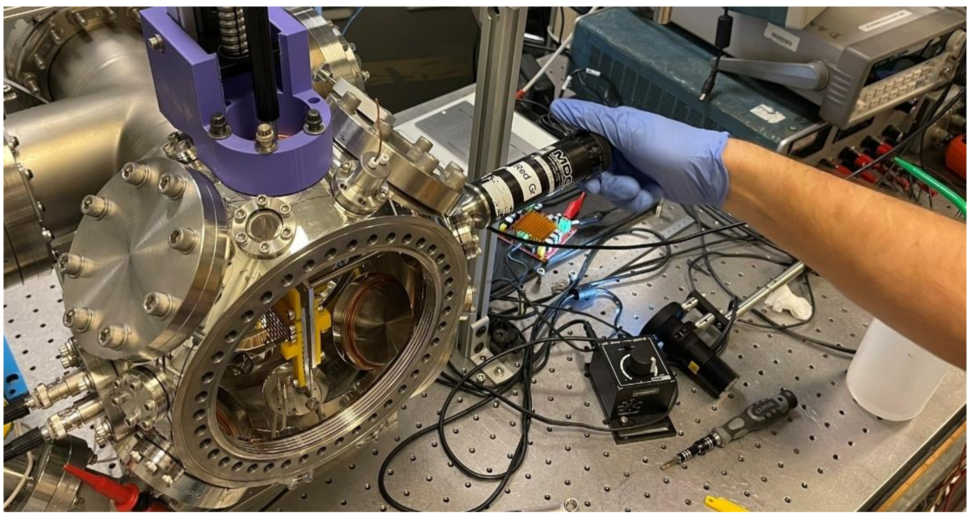


Figure 35: Demonstration of Variable Bend Radius

Another consideration for the industrial design of the test fixture was how technicians/graduate students would interface with the clamping fixture. Initial testing revealed that doing all the clamping and positioning of the EDS to the fixture should be done out of the vacuum chamber. This is due to the size constraints of the vacuum chamber and the difficulty of fastening bolts in awkward positioning. A further revision of the mounting plate made this easier to do outside of the chamber, adding to the usability of the design.

Engineering Analysis and Experiments

To ensure that the proposed design for the testing rig meets specifications, there are 2 primary forms of engineering analyses to be performed – fatigue from the cyclic loading the rig enacts on the EDS to determine part lifetimes and bending/deflection testing from the device's weight to determine the necessity of extra mounting. The part most likely to suffer from wear or fatigue in cyclic loading is the lead screw that adjusts the variable bending radius of the test. Metallic lead screws, which are required in the high vacuum setting, are typically lubricated to reduce wear from metal-on-metal sliding contact. However, lubricants cannot be used within the setting of the vacuum chamber, so it is significantly more susceptible to frictional wear than is standard. Once a motor is officially selected, analysis will be done to determine the extent to which the lead screw is damaged in this setting.

The other critical consideration is the bending stress and deflection caused by the rig's weight. The mounting tools available in the setup provided by GT CLEVER's lab currently consist of two sets of Groove Grabbers – devices mounted within the flanges of the vacuum chamber that have threaded openings and mounts of up to 1/8". This is a reliable form of mounting, but one set is being used for the regolith dust dropper leaving one remaining for the rig's mounting, and with significant price and lead time considerations, ordering more may not be feasible. Due to this, it is imperative to determine if the current setup's deflection falls within the allowable range - 1/10 of the size of the bending radius – to be deemed unimpactful in data acquisition. This was done via FEA in Siemens NX's Simcenter with simplifying assumptions of neglecting contact stresses by joining components together, and preliminary estimates on the materials used and motor selected. There is an ongoing discussion on whether the EDS will be powered during testing and if the thin layer of film on top of the substrate insulating the circuit will be in place, both of which will affect material usage and could alter the results. The constraints applied are in all 6 translational/rotational DOF at the end of the mounting rods that intersect with the groove grabber, similar to a cantilever beam. There is an additional constraint about the plane of symmetry that the device was split in half about (to reduce computational time) to account for the unmodeled half. The applied load is simply the weight of the device. As shown in Figure. 18, these parameters yielded a maximum deflection of 0.00103 mm for the testing configuration of 5 mm, only 0.021% of the desired bending radius, well within the acceptable margins.

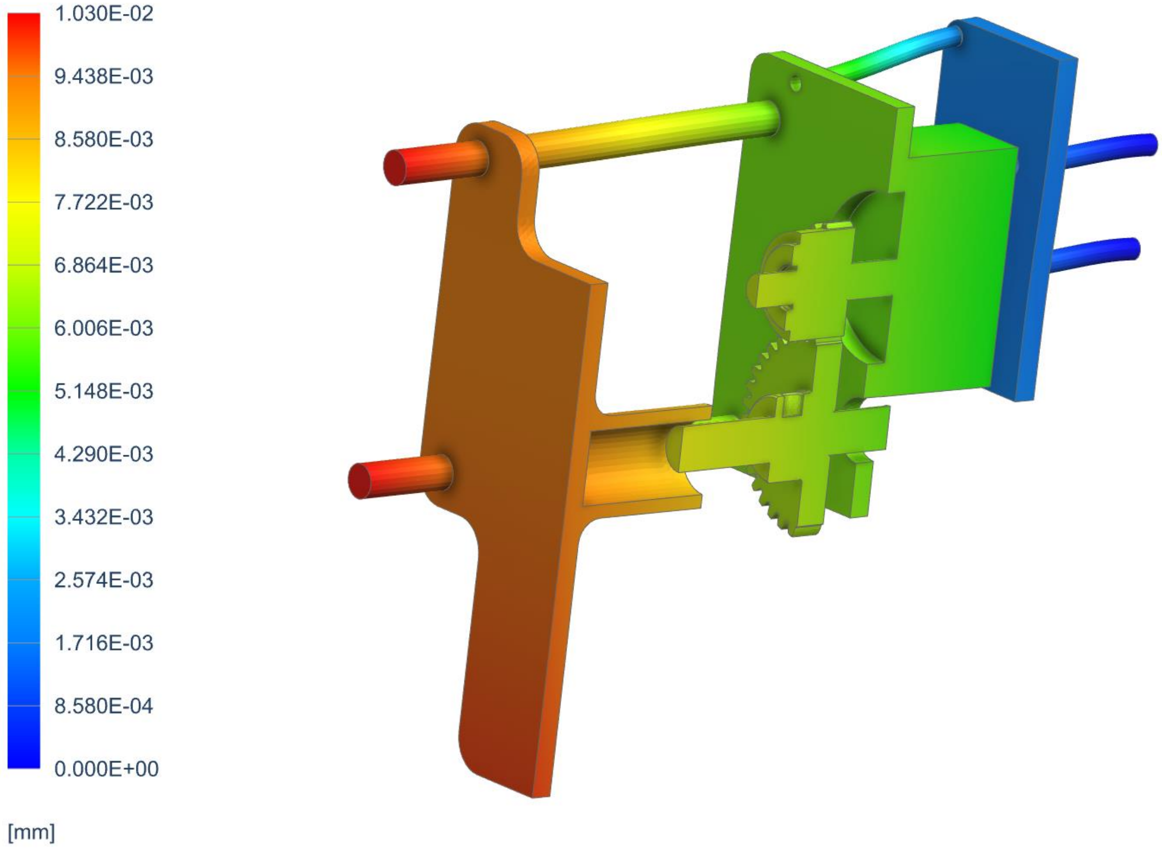


Figure 36: Deflection FEA of Testing Rig

Mockup and Prototyping

Team Joint Discovery's final form of the recommended test setup involves two ultra-high vacuum rated linear actuators; however, due to the lead time and expenses associated with ordering one, a prototype was developed to perform testing in a non-vacuum rated setting as a proof of concept. To optimize manufacturing speed, the internal mounting depicted in Figure 37 were 3D-printed, except for the primary support plates which required more stiffness than PLA would provide. Additionally, a simple strip of PDE was used as opposed to a sample of EDS, as power was not running and current lengths of the EDS would not showcase the full capabilities of the adjustable bending radius. Combined, they produce a robust prototype for testing, suitable for providing validity to the recommended stock purchases and machining efforts necessary in a vacuum rated version.

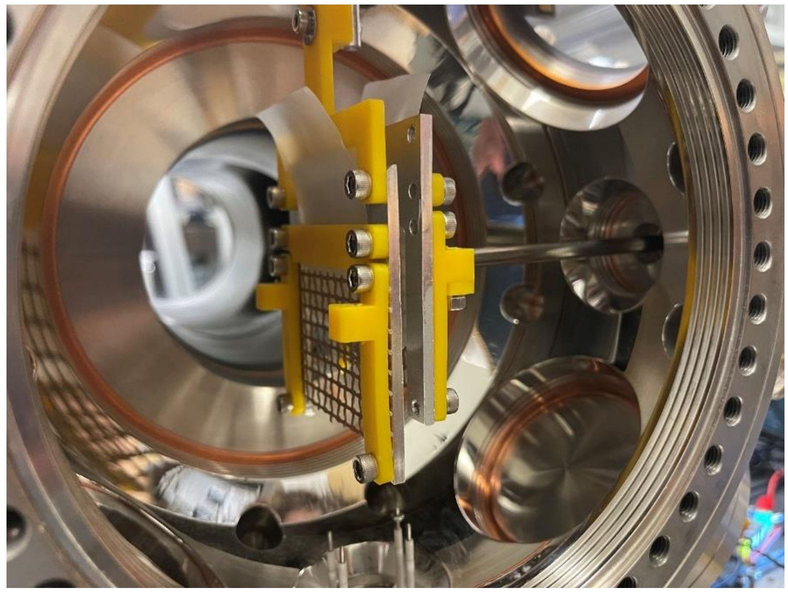


Figure 37: Non-Vacuum Rated Testing Prototype Internal Components

External to the vacuum chamber was a high-fidelity prototype linear actuator, depicted in Figure 38 designed to be retrofitted to the lab's current UHV linear actuator from MDC Precision. Key factors that were considered in the design of the prototype were replicating the stroke length, internal mounting interface, flange interface, and ensuring the linear actuating motion was central to the flange it was

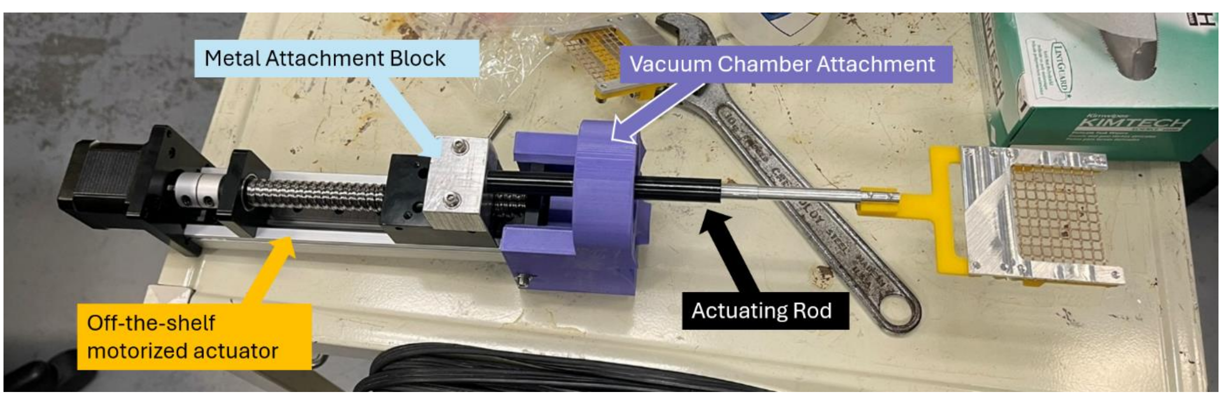


Figure 38: High Fidelity Prototype

mounted to. An off-the-shelf linear actuator was purchased, selected for its axial load bearing capabilities, precise stepper motor, and robust mounting capabilities.

To replicate the stroke length, minimum and maximum positions were programmed to the stepper motor attached to the purchased linear actuator, although in full testing, limit switches will be implemented for more reliable results. The internal mounting system on the UHV actuator involved a 0.25” diameter rod, faced down ~0.2” from the end of the rod for 0.75”, and two 6-32 holes. This was recreated with aluminum rod stock of the same length, lathed down to the appropriate diameter, faced down and tapped on the mill. Mirroring the flange interface and aligning the prototype actuating rod were done with a custom 3D-print shown in Figure 37. Its features include a face with the same necessary mounting dimensions as the DN16CF on the UHV linear actuator, but with a smaller inner diameter to avoid infringing upon the delicate knife edge on the vacuum chamber’s flange.

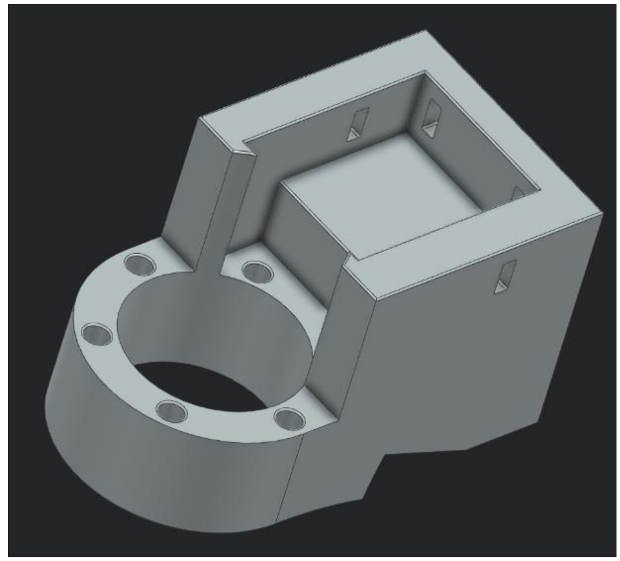


Figure 39: 3D-Printed Flange Interface and Linear Actuator Mount

To ensure a known alignment of the actuator, the print also included a slot for the purchased linear actuator with an interference fit, highlighted in Figure 39, and slots to further secure it with threaded fasteners. Then to make the rod align in the middle of the flange, the aluminum stock connecting the actuating rod to the guided mount on the actuator was machined down to the appropriate height. Maintaining stability was also crucial for the demonstration, so the part is curved to maintain more surface contact with the vacuum chamber and has extrusions to allow it to sit on existing flanges, depicted in Figure 40. The result was a robust prototype linear actuator with the necessary features and testing capabilities to recommend a known UHV counterpart.

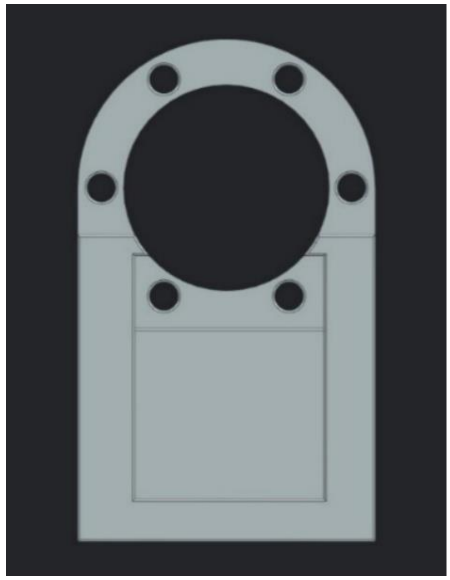


Figure 40: Side View of 3D-Printed Flange Interface and Linear Actuator Mount

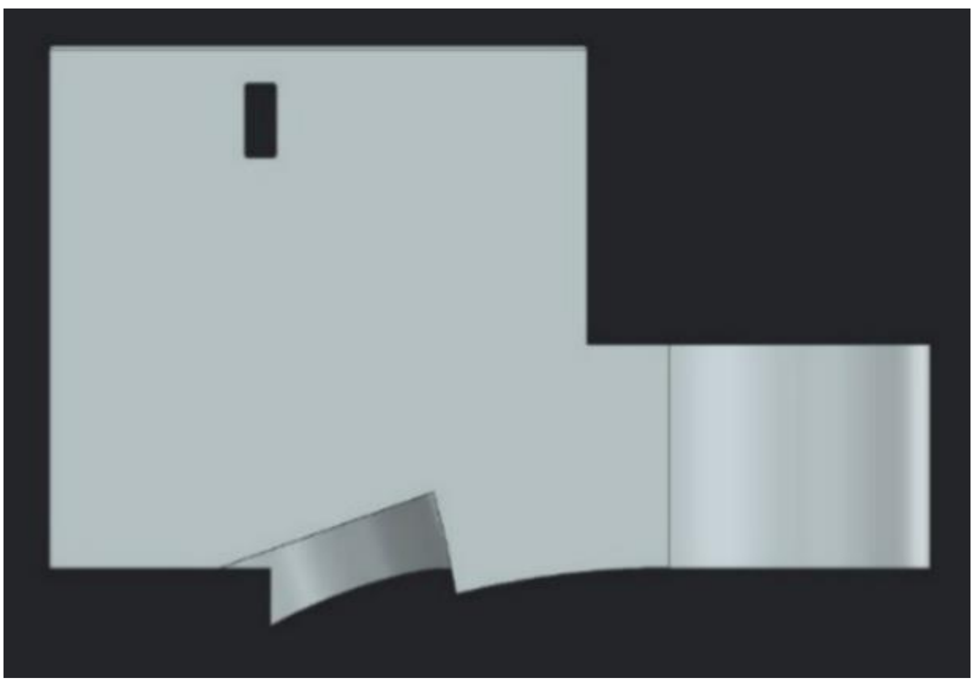


Figure 41: Side View of 3D-Printed Flange Interface and Linear Actuator Mount

Final Design

The final design for the system consists of two subassemblies, each actuated with a linear passthrough into the chamber. By taking advantage of off-the-shelf, vacuum rated passthroughs, the team was able to simplify the design and improve reliability. Each linear passthrough is rated to a vacuum of 10^{-8} torr, which is sufficient for the needs of the client. The vertical passthrough is motorized to allow for automated sweeping and cyclic repetition of the film. This will be seamlessly integrated with the LabVIEW interface for simple control.

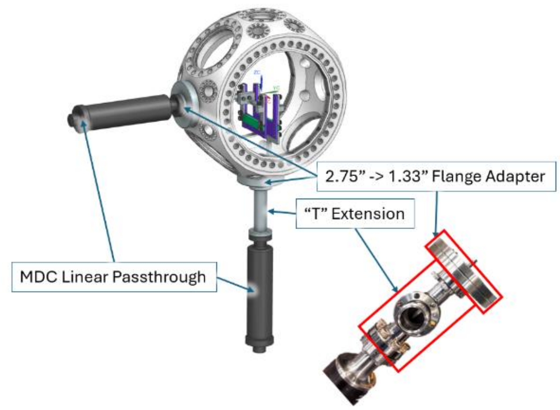


Figure 42: Full assembly with linear

The horizontal actuation is used to adjust the film bending radius, which is a requirement to accurately test the chosen standard. This actuation is done by hand using the horizontal linear passthrough, which can be accurately determined by first zeroing the plates by touching them together and then backing off to the desired bend radius. It should be noted that the horizontal passthrough stroke is directly tied to the diameter of the film, ex. a 10mm backout of the actuator results in a +5mm bend radius. The smallest bend radius, when the two plates are touching, is 2mm, as mandated by the minimum thickness of the film plates during manufacturing.

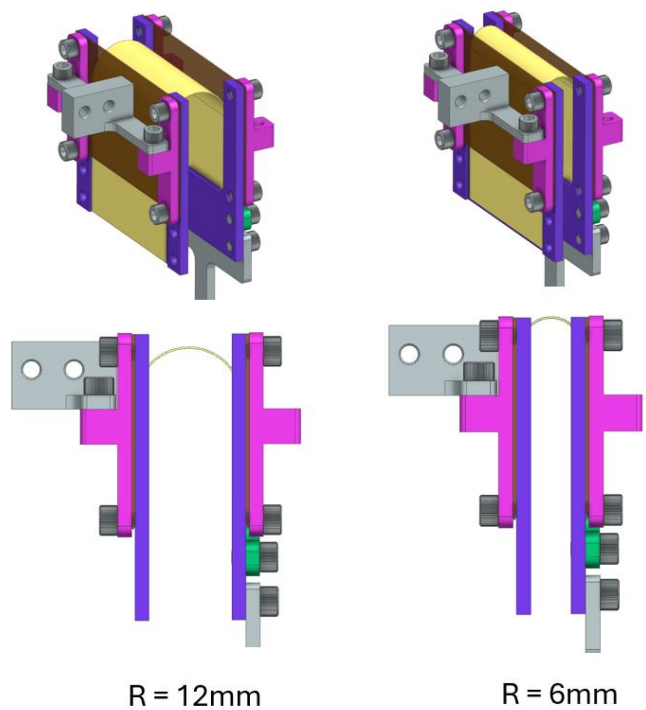


Figure 43: Variable adjustment of bending radius using Horizontal Actuation

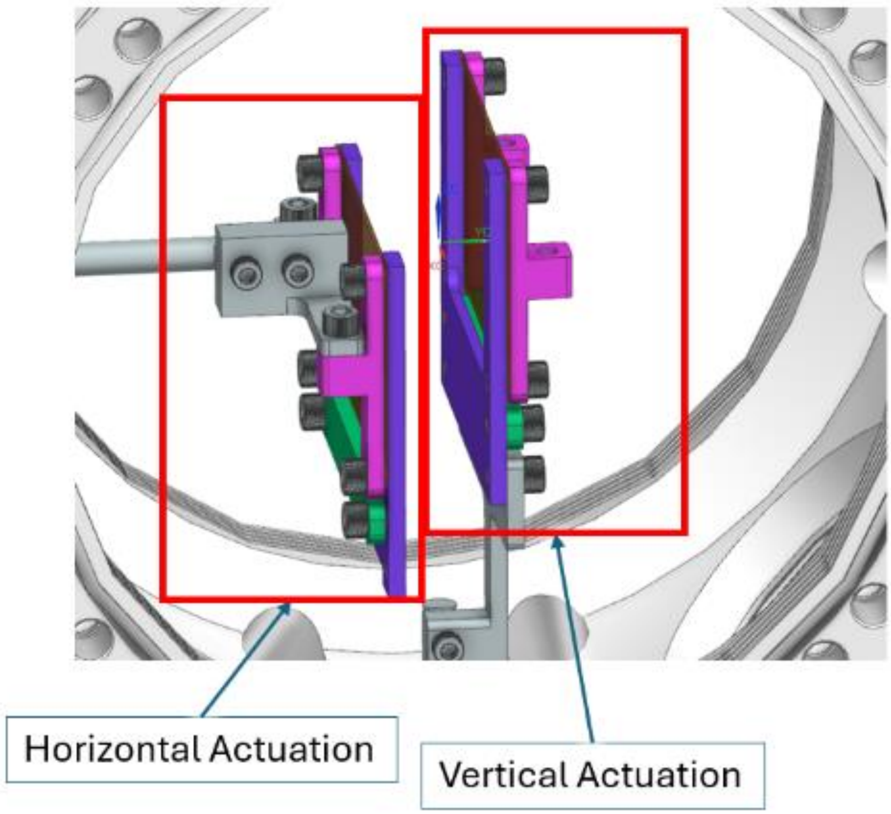


Figure 44: Horizontal and Vertical actuation subassembly closeups

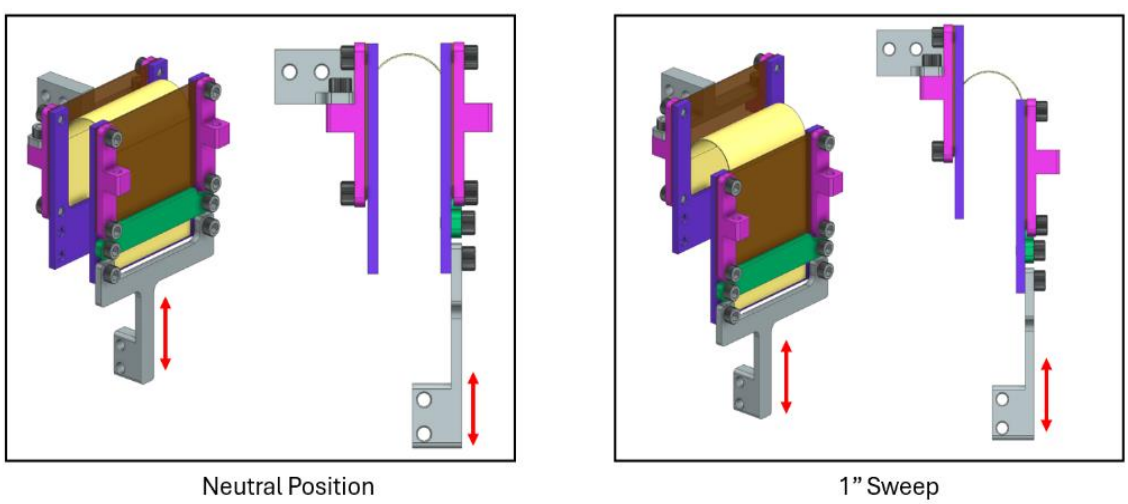


Figure 45: Linear motion performed by Vertical Actuation

The vertical actuation is the main sweeping motion, which repeats for any number of cycles to meet the client's requirements. The vertical actuation is motorized, and can perform any number of cycles. It is important for the user to properly setup up the actuation restriction zones, so the assembly does not over-extend and clash the fixture into the chamber.

The system was designed to fit within the chamber and not occlude the Dust Falling System (DFS), but has a larger stroke length without the DFS installed. The final capabilities are listed below. The only original requirement that was unmet by the system is for the stroke length, which falls slightly below 2". This is due to a limitation of the linear actuator and packaging of the device under the DFS, but it will still be proficient for the client's needs.

Table 4: Customer Required Dimensions

Dimension	Capability	Requirement
Stroke Length	45mm (1.8")	2"
Min Radius	2mm	2mm
Max Radius	13.5mm	10mm
Max Film Width	53mm	50mm

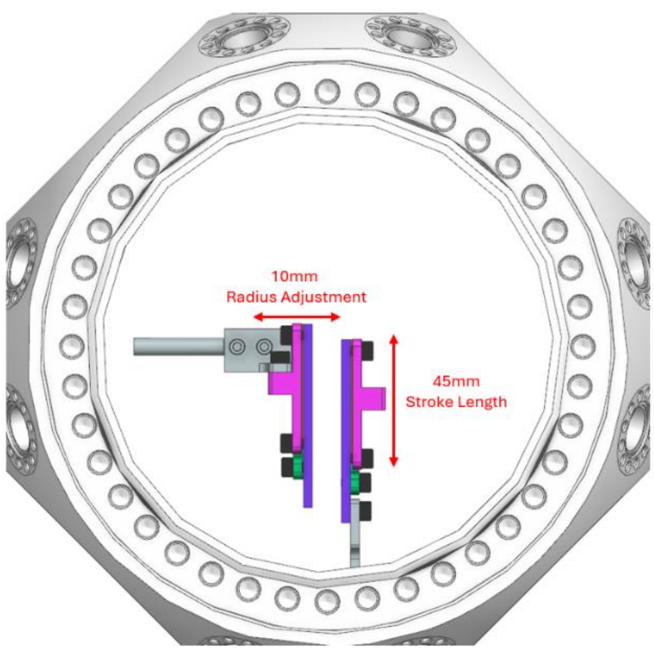


Figure 46: Vertical and Horizontal adjustment ability

After the initial vacuum chamber test, the team found it was difficult to properly assemble the device within the chamber due to limited access. Furthermore, the client brought to attention the need to assemble the film into the clamping device *before* being installed in the chamber, as this will reduce the risk of damage to the electrical leads. The horizontal and vertical mounts have been designed to allow easy mounting to the linear actuators after the film has been attached. The bolts are conveniently oriented to allow tightening from opening in the main chamber.

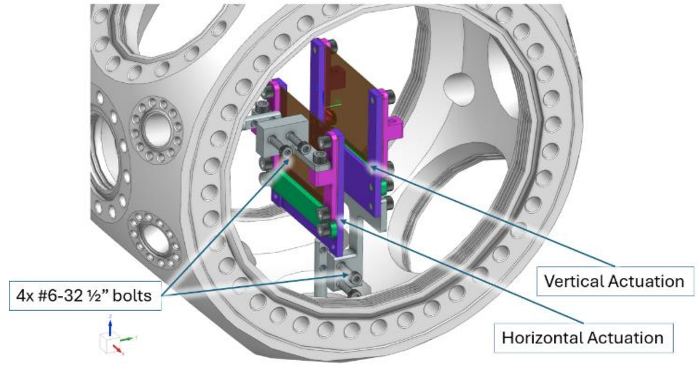


Figure 47: Installation of Horizontal and Vertical actuations assemblies into chamber

Assembly of each sub-assembly is simple, requiring only a few screws and the machined pieces. The mesh is held tightly in place by the mesh clamps, which act to clamp the fiberglass fabric down to the film plate. This method allows easy changing of mesh materials if desired, and provides a rigid mechanical connection that avoids adhesives which may lead to unfavorable results in ultra-high vacuum conditions. The purpose of the fiberglass fabric is to prevent buildup of lunar regolith during falling. The mesh pictured in the CAD is solid, but the real mesh is showed below.

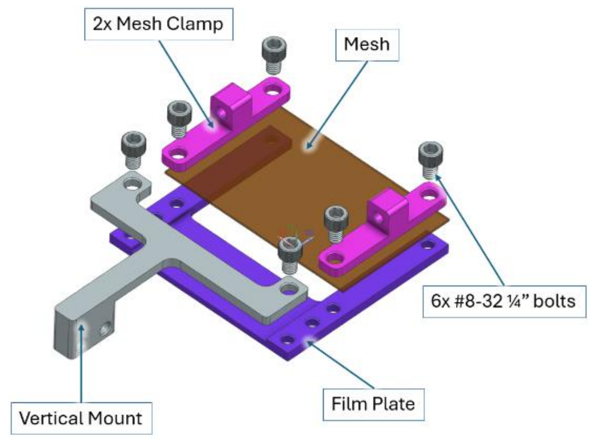


Figure 48: Assembly of Mount and Mesh using Mesh Clamps

It was important for the client to have a strong mechanical connection holding the film in place. Previous methods included using a double sided tape, but to ensure a strong consistent connection through multiple cycles, the team implemented a clamping method.

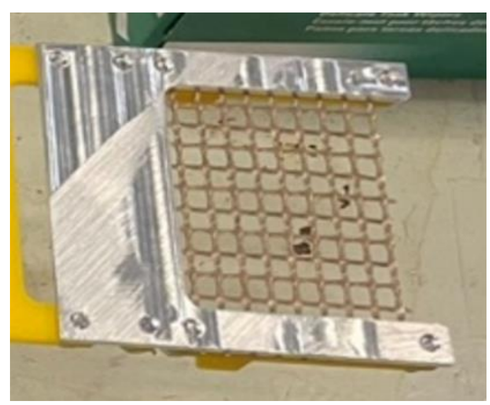


Figure 49: Mesh installed on prototype assembly

All of the parts are either bought off the shelf (COTS) from a supplier or need to be machined out of aluminum. Below is an example of a drawing that can be directly given to a machine shop to produce the required part. The full set of drawings and links to COTS are found in the final fabrication package, including the full BOM.

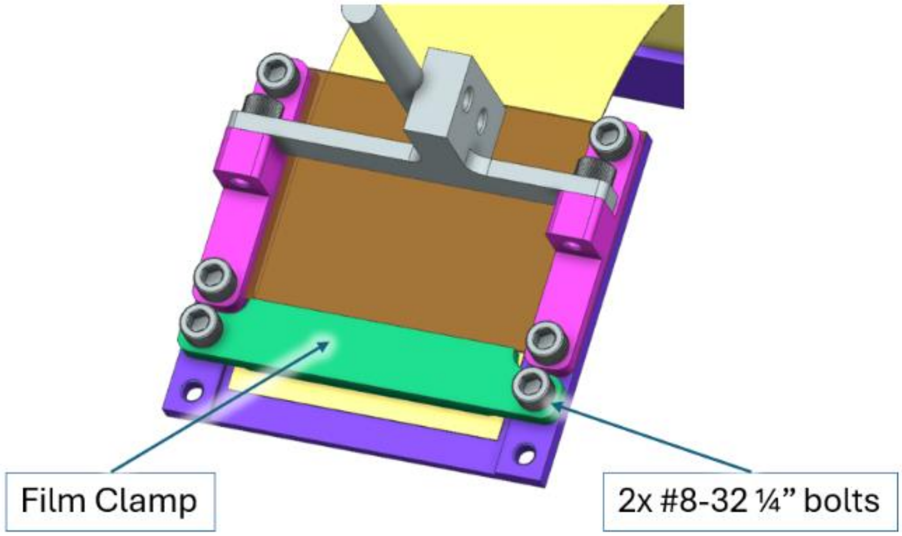


Figure 50: Film fully installed on horizontal actuation

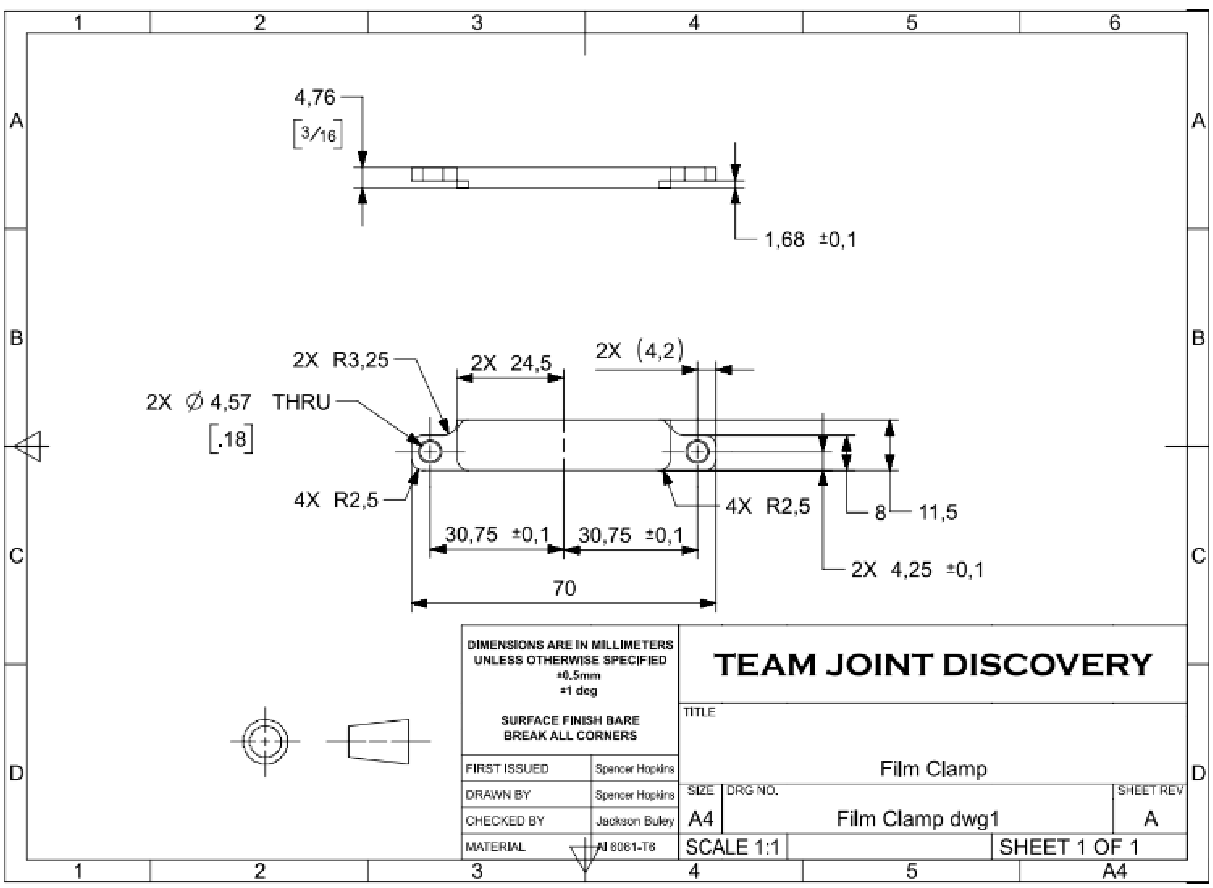


Figure 51: Engineering drawing for Film Clamp

Manufacturing

Design for manufacturing was a critical element of the project throughout all stages of development. Even though the final product is not intended to be mass produced, manufacturing is still a critical element of the overall design considerations. Namely, because of the vacuum environment, the final product had to be machined from metal. This is because metals do not experience outgassing effects that could damage the internal equipment inside the vacuum chamber.

For prototyping, this was not a major concern as the initial testing was conducted in ambient conditions. As such, the initial design could be 3D printed from standard PLA to reduce cost and time from manufacturing with metal. While the prototyping provided a physical way to validate the geometry of the components together, the resolution of the printer was too low to allow for any threaded connections.

Purchasing a vacuum-rated linear actuator was too expensive for the prototype budget. Because of this, team JD designed a non-vacuum rated linear actuator that could be put in place. The non-vacuum rated actuator needed to have the same dimensions as the vacuum rated counterpart to validate the overall system could function. In the end, the design for the prototype actuator consisted of 4 parts: off the shelf motorized actuator, metal connecting block, vacuum chamber mounting flange, and actuating arm.

The tolerances on the manufacturing of the prototype linear actuator were very tight; within ±0.05mm for spacing between holes (tightest parameter) and ±0.5mm for overall size dimensions. Both the metal connection block and actuating rod were machined out of aluminum stock using the Montgomery Machining Hall. While it is not necessary for the final product, these machined parts were critical for the prototyping to ensure the system could function properly. At the end of the actuating rod were two holes that needed to be machined to closely match the connection points of the vacuum rated actuator. Special care and attention were taken to ensure the tolerances fell within the allotted ±0.005” and the overall system could be connected to it.

Furthermore, while parts of the mounting plate were 3D printed from PLA material, the final product will have to be machined from aluminum stock. As such, when designing the final product, care was taken towards designing the overall plate to be flat and easily machined. It used standard threaded connections that are repeated throughout the design of the mounting plate so no more than one tap must be used.

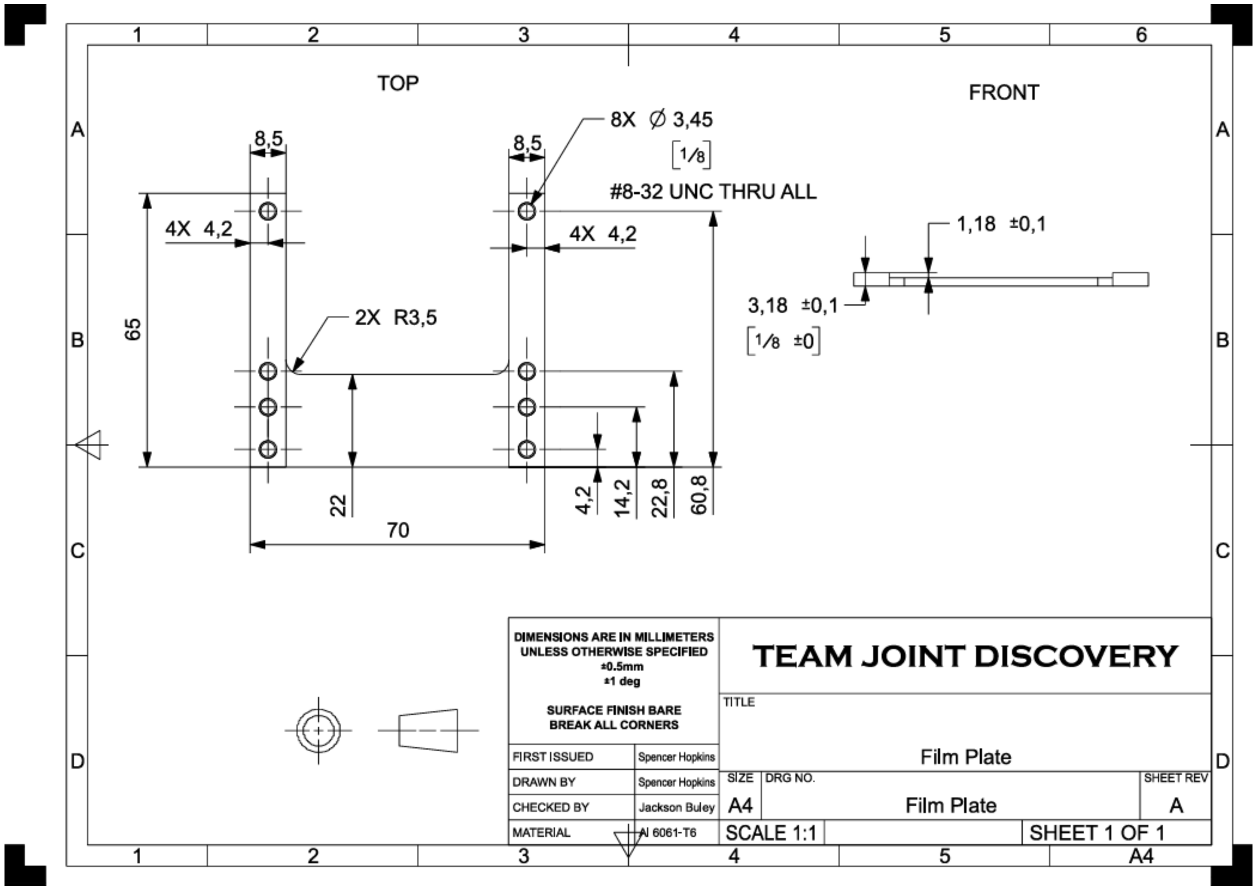


Figure 52: Engineering Drawing for Film Plate

When designing the final film plate, team JD was able to construct their own threaded connections and through holes. As such, the tolerancing on the final product is ±0.5mm. However, the thickness of the part must be machined to within ±0.1mm. This is because the height of the film plate is crucial to know the bend radius of EDS accurately.

Figure 53: Machining the Film Plate

Overall, the part was designed to be machined from standard aluminum stock (Al 6061). The material is relatively low cost and easily obtainable for manufacturing. It is one of the most common aluminum alloys used in general purpose machining, such as this. Al 6061 also has the added benefit of use in an ultra-high vacuum environment. Because of its abundance and ease in machining, this alloy was selected as the material for the final product.

Societal, Environmental, and Sustainability Considerations

This section will implement the Social Impact Assessment as outlined in the ME Capstone website (Social Impact Assessment (SIA) for Capstone Design, 2020).

1. Goal and Scope

This section depicts the goal and scope of the Social Impact Assessment.

Table 5: Goal and Scope Section Summary

<table>
<tr><th>Objective of Assessment</th><th>Design Function</th><th>Functional Unit</th><th>Lifecycle Stages Considered</th><th>Associated Activities</th></tr>
<tr><td rowspan="5">Assess the societal impacts of a flexible EDS for lunar applications</td><td rowspan="5">Repel lunar regolith from flexible/curved surfaces.</td><td rowspan="5">A strip of flexible EDS</td><td rowspan="3">Production</td><td>The creation and production of the EDS</td></tr>
<tr><td>Test and validation of EDS</td></tr>
<tr><td>Local job creation</td></tr>
<tr><td>Use</td><td>The effectiveness of the EDS on the moon</td></tr>
<tr><td>End-of-life</td><td>Not creating lunar waste</td></tr>
</table>

2. Societal Impact Categories and Indicators

This section discusses the social impact categories and impact indicators.

Table 6: Inventory Analysis Section Summary

Lifecycle Stage	Stakeholder Group	Social Impact Category	Impact Indicators
Production	Worker	Health and Safety	Appropriate protective gear required in all applicable

			situations
			Occupational accident rate
	Worker	Health and Safety	Presence of a formal policy concerning health and safety
			Adequate general occupational safety measures are taken
	Local Community	Local Prosperity	Creation of high-tech jobs
Use	Consumer	Feedback Mechanism	Investment in local R&D infrastructure
			Number of consumer complaints per square foot of EDS installed
End-of-life	Society (Humanity)	Transgenerational Responsibility	Presence of a decommissioning plan/adherence to "leave no trace" principles on the Moon

3. Reflection on Societal Impacts

The evaluation and eventual end use of a flexible EDS will have a net positive impact on humanity's wellbeing with some potential negative impacts that require mitigation.

The primary impact is that this will provide safeguarding of both humans who are interacting with objects that are protected using a flexible EDS as well as by ensuring mission success of components that would suffer from the presence of lunar dust. Further, this project would further stimulate high-tech job creation and research and development infrastructure as generated during the production and test life cycles of the project. By attempting to produce the least amount of additional lunar waste (by the nature of flexible EDS being a solid-state device), this project emphasizes the principle of transgenerational responsibility by preserving the lunar environment.

There are potentially negative impacts from this project, including worker safety. During the production and testing stages, the workers will be handling specialized materials/chemicals as well as being potentially exposed to high voltage. If the flexible EDS ends failing before their expected life cycle, it could potentially contribute to increased lunar waste as well as impacting the lifespans of the objects/devices it is intended to protect.

This section focused on the production, use, and end-of-life lifecycle stages as they represent the most socially consequential phases of this technology. The stakeholder groups were selected based on those directly affected by the technology, such as the workers developing and producing the technology. The stakeholders further include the consumers who are the direct beneficiaries of their functionality, and then the larger scale societal impacts are considered as well. Indicators and categories were selected to map measurable outcomes and goals for the selected stakeholders.

Risk Assessment, Safety and Liability

Potential risks stem from the recommended vacuum rated testing procedures. Artificial regolith poses a significant hazard to human health if released breathed in or ingested. GT CLEVER must follow the safety procedures associated with the loading and use of the dust dropping mechanism. Additionally, if testing is run when the EDS is powered, there must be measures taken to avoid either contact between the conductive grid or effectively ground the current. This affected the design of the internal mounting components in recommending the use of alumina for a less conductive material, and in providing another reason to using and actively powered EDS in testing.

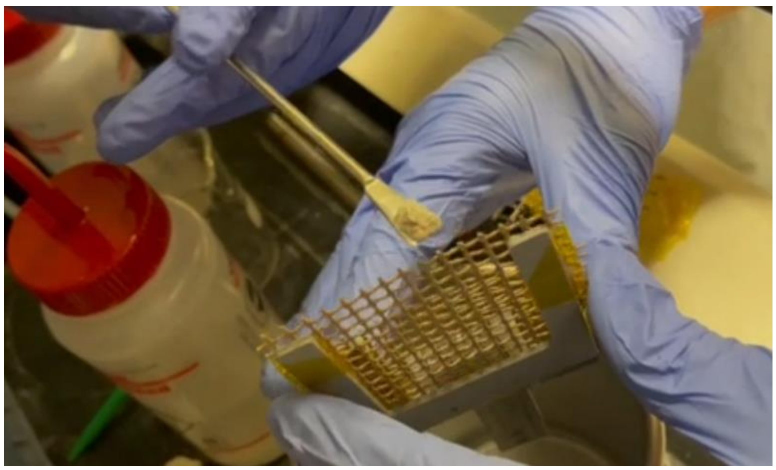


Figure 54: Testing with the Lunar Simulant Requires Gloves and Fume Hood to Prevent Exposure

Team JD also took care of prototyping to avoid damaging the vacuum chamber due to its significant cost and necessity in GT CLEVER's research. Certain components of the UHV linear actuator's flange interface were not replicated in the 3D printed replica to avoid unnecessary contact with the knife edge on the chamber's corresponding flange. If the chamber was damaged, it would negatively impact the overall vacuum rating and cost the lab potentially thousands of dollars to repair. Additionally, the internal mounting system applied crucial design for assembly features in applying appropriate spacing between the parts and the external walls of the chamber to prevent contact when assembling.

During prototyping, it was found that manually setting the limit switches proved to be difficult. This resulted in the need for a "kill switch", a simple on/off switch that could turn off the mechanism in an instant. This was necessary so that the actuator did not extend far enough to touch the vacuum chamber walls and/or damage the chamber walls. While critical for the prototyping phase, the use of limit switches in the final product will eliminate the need for this fail-safe. Limit switches provide a physical barrier for the actuator to prevent it from extending too far inside of the chamber.

Patent Claims and Commercialization

Team JD has no patent claims over our design. The team believes that by keeping the design open source, it will enable researchers to iterate over our design and make improvements to enable EDS studies while the system is powered. This report, and all associated documents will be hosted on a public GitHub repository available here: https://github.com/s-callaway/Team-Joint-Discovery-Bending-EDS

In addition, the team has no plans or prospects for commercialization. The team hopes to help researchers progress in the field of electrodynamic shielding. The only opportunity the team is considering is recognition in any journal that future work may be published involving the bending prototype the team developed.

Team Member Contributions

Jackson Buley (Mechanical Engineering): Jackson Buley worked closely with Drew Peljovich to distill House of Quality, FMEA, and specifications documents from our sponsor meetings. He also performed the FEA and engineering analysis. Jackson also contributed to the design of the linear actuator mount that imparted bending on the EDS.

Drew Peljovich (Mechanical Engineering): Drew led the writing and presentation work. He distributed the report work and worked closely with Jackson Buley to complete the House of Quality, FMEA, and Spec sheet. Drew created the LabVIEW interface for our clients (the graduate students) to autonomously control the stepper motor. In addition, he and Jackson worked together to machine or final design parts.

Spencer Hopkins (Mechanical Engineering): Spencer developed the in-depth drawings and developed the CAD for the final design. Spencer developed and printed our final prototypes as well. Spencer conducted much of the original work into standards research and led the mechanical design to meet customer requirements.

Vikas Muralidharan (Material Science and Engineering): Vikas acted as the project manager and gave insight into the uses and materials of the EDS device. He developed the Gantt chart as well as helped Jackson Buley set up meetings with sponsors. He also developed the poster for the capstone expo.

Sasha Callaway (Computer Engineering): Sasha Callaway contributed the bulk of the market research for EDS and helped iterate one potential design choice given his background with PCB's. He further did research into the flexible PCB related standards and implemented the social impact assessment. He wrote the budget appendix, existing products and prior art, as well as industrial design.

Summary and Future Work

In summary, Team JD has successfully designed a compact, vacuum-compatible bending rig for flexible EDS films. The primary challenge of this project was to design a repeatable bending mechanism that could operate under ultra-high vacuum while accommodating limited electrical passthroughs and mechanical interfaces. To address this, the team developed a rig that leverages the existing linear bellows drive to cyclically bend the EDS film, ensuring both repeatability and cost efficiency. The design successfully balances the chamber's strict constraints with functional requirements, allowing for simultaneous dust deposition and electrical activation of the EDS. This rig serves as a critical proof-of-concept platform for validating flexible EDS technology, advancing its readiness for commercialization and deployment in lunar missions. Unlike prior art, it uniquely addresses cyclic bending of flexible thin-films in vacuum, filling an important gap in current testing systems.

The next steps for this project involve fabricating the rig and conducting experimental validation under vacuum, including cyclic bending with dust deposition and EDS activation. Long-term durability studies, such as testing beyond 1,000 cycles, will be needed to assess fatigue resistance and cleaning efficiency. Incorporating cameras and sensors will enable real-time monitoring of dust removal and bending performance, while future design refinements may explore modularity to allow variable bending radii, torsional loading, and integration with larger chamber setups.

To prepare the system for the vacuum environment, all the materials that exist directly inside the vacuum chamber must be machined from an aluminum alloy to withstand the extreme low-pressure conditions using the fabrication package. Furthermore, purchasing one motorized linear actuator is necessary to perform cyclic bending in the vacuum environment. Standoffs need to be incorporated into the design to raise the vacuum chamber and mount the vertical linear actuator underneath to allow for dust deposition in the process. Exact dimensions cannot be determined until a quote is requested for the part, as the manufacturer does not provide that information readily. The final change would be the addition of limit switches to provide more robust control near the minimum and maximum displacement. These switches have bolt holes for securing to the linear actuator and will be pressed by the linear actuator's position indicator. The code for implementing these switches already exists in the Arduino code, but the physical implementation is needed.

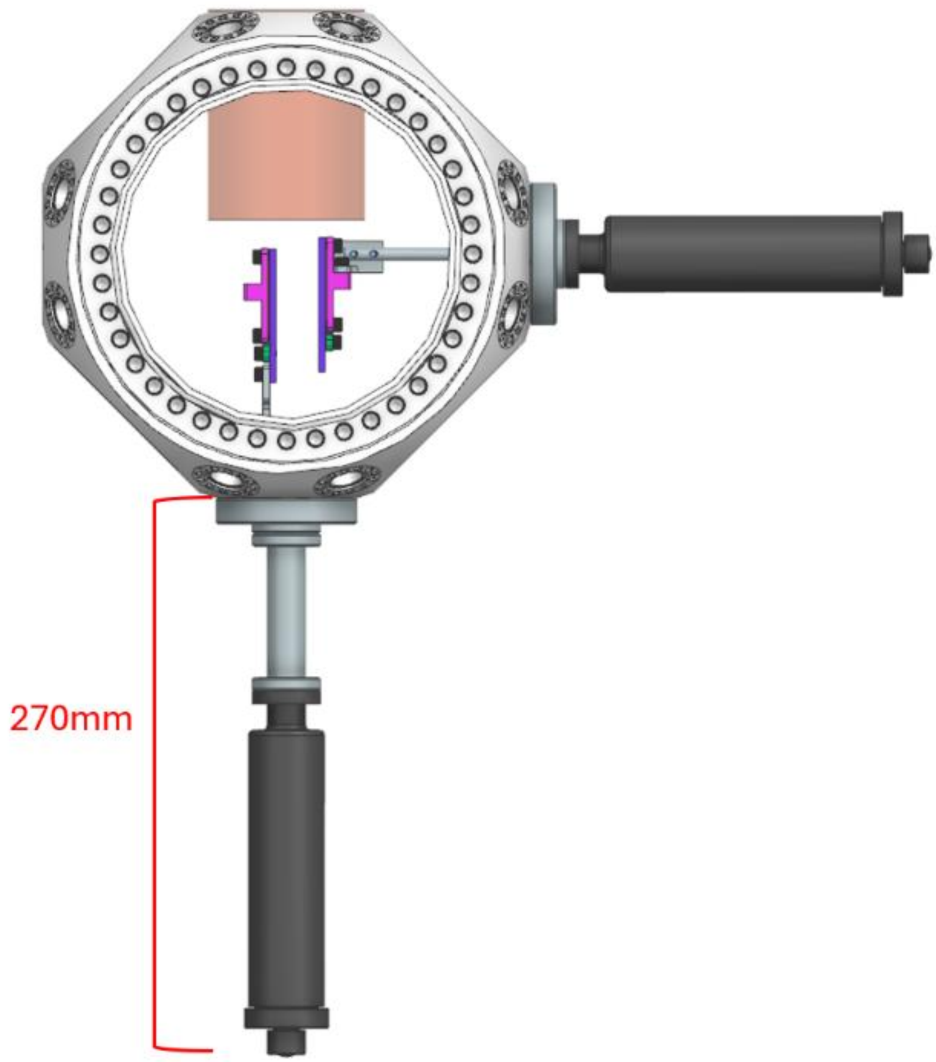


Figure 55: Height of bottom linear actuator as modeled with non-motorized actuator

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Appendix

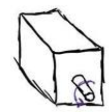
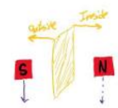
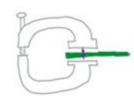
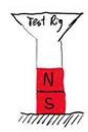
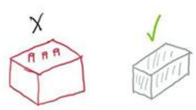
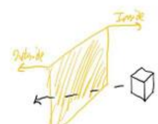
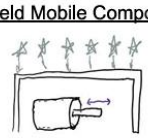
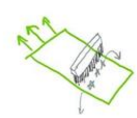
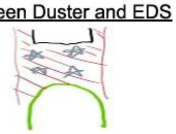
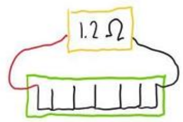
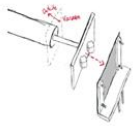
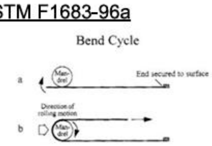
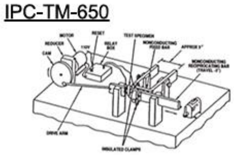
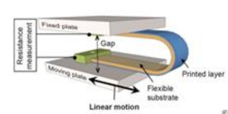
Sub Function	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Motion Actuation	Linear Actuator Operated 	Rotary Actuator Operated 	Internal Motor Powered 	Magnetic Coupling 
EDS Mounting	Fasten with Nuts/Bolts 	Secure with Adhesive 	Clamp Substrate 	
Test Rig Mounting	Groove Grabbers 	Magnetic Mounting 	Vacuum Rated Epoxy 	
Prevent Off Gassing	High Vacuum Rated Parts Selected 	Reduce Components in Vacuum 		
Avoid Damage from Regolith Wear	Shield Mobile Components 	Possess Sufficient Hardness 	Regolith Sweeping 	
Data Collection	Maintain Clear Path between Duster and EDS 	Measure Resistivity of Substrate 	Maintain Line of Sight of Substrate from Camera 	
Adhere to a Standard	ASTM E855 	ASTM F1683-96a 	IPC-TM-650 	IEC-62899-202-5 

Figure 56: Full Morphological Chart

ESP32-C6											
J1 USB						J3 UART					
Connection	Breadboard Connection	Breadboard	Type	Name	No.	No.	Name	Type	Breadboard	Breadboard Connection	Connection
NC	NC	A_B_21	P	5V	1	1	5V	P	A_T_21	NC	NC
Left breadboard Ground	A_B_-	A_B_22	G	GND	2	2	13	I/O/T	A_T_22	B_T_9	DIRECTION_A
NC	NC	A_B_23	I/O/T	9	3	3	12	I/O/T	A_T_23	B_T_10	STEP_A
Limit Switch A	A_T_9	A_B_24	I/O/T	18	4	4	11	I/O/T	A_T_24	B_T_12	nRESET_A
Limit Switch B	A_T_12	A_B_25	I/O/T	19	5	5	10	I/O/T	A_T_25	B_T_16	nENABLE_A
NC	NC	A_B_26	I/O/T	20	6	6	8	I/O/T	A_T_26	NC	
NC	NC	A_B_27	I/O/T	21	7	7	1	I/O/T	A_T_27	B_T_19	DIRECTION_B
NC	NC	A_B_28	I/O/T	22	8	8	0	I/O/T	A_T_28	B_T_20	STEP_B
NC	NC	A_B_29	I/O/T	23	9	9	7	I/O/T	A_T_29	B_T_22	nRESET_B
NC	NC	A_B_30	I/O/T	15	10	10	6	I/O/T	A_T_30	B_T_26	nENABLE_B
EMPTY			I/O/T	RX	11	11	5	I/O/T	EMPTY		
NC	NC	B_B_1	I/O/T	TX	12	12	4	I/O/T	B_T_1	NC	NC
NC	NC	B_B_2	I/O/T	3	13	13	RST	I	B_T_2	NC	NC
NC	NC	B_B_3	I/O/T	2	14	14	3V3	P	B_T_3	B_T_+	Right Breadboard Plus
Right Breadboard Ground	B_B_-	B_B_4	G	GND	15	15	GND	GND	B_T_4	B_T_-	Right Breadboard Ground

A4988 Driver A (TOPSIDE)											
J1						J2					
Connection	Breadboard Connection	Breadboard	Type	Name	No.	No.	Name	Type	Breadboard	Breadboard Connection	Connection
G_ESP	B_B_-	B_B_9	G	GROUND	1	1	DIRECTION_A	I	B_T_9	B_T_1	12_4_ESP
3V3_ESP	B_T_+	B_B_10	P	VDD	2	2	STEP_A	I	B_T_10	A_T_23	7_21_ESP
1_B_M_A	B_B_11	B_B_11	O	1B	3	3	nSLEEP_A	I	B_T_11	B_T_10	STEP_A
1_A_M_A	B_B_12	B_B_12	O	1A	4	4	nRESET_A	I	B_T_12	A_T_24	4_11_ESP
2_A_M_A	B_B_13	B_B_13	O	2A	4	4	MS3_A	I	B_T_13	NC	NC
2_B_M_A	B_B_14	B_B_14	O	2B	5	5	MS2_A	I	B_T_14	NC	NC
G_M	B_T_-	B_B_15	G	GROUND	6	6	MS1_A	I	B_T_15	NC	NC
VMOT_M		B_B_16	P	VMOT	7	7	nENABLE_A	I	B_T_16	A_T_25	5_10_ESP

A4988 Driver B (TOPSIDE)											
J1						J2					
Connection	Breadboard Connection	Breadboard	Type	Name	No.	No.	Name	Type	Breadboard	Breadboard Connection	Connection
G_ESP	B_B_-	B_B_19	G	GROUND	1	1	DIRECTION_B	I	B_T_19	A_T_27	7_1_ESP
3V3_ESP	B_T_+	B_B_20	P	VDD	2	2	STEP_B	I	B_T_20	A_T_28	8_0_ESP
1_B_M_B	B_B_21	B_B_21	O	1B	3	3	nSLEEP_B	I	B_T_21	B_T_20	STEP_B
1_A_M_B	B_B_22	B_B_22	O	1A	4	4	nRESET_B	I	B_T_22	A_T_29	9_7_ESP
2_A_M_	B_B_23	B_B_23	O	2A	4	4	MS3_B	I	B_T_23	NC	NC
2_B_M_B	B_B_24	B_B_24	O	2B	5	5	MS2_B	I	B_T_24	NC	NC
G_M	B_T_-	B_B_25	G	GROUND	6	6	MS1_B	I	B_T_25	NC	NC
VMOT_M		B_B_26	P	VMOT	7	7	nENABLE_B	I	B_T_26	A_T_30	10_6_ESP

Figure 57: ESP32 Based Motor Controller Board Pinout (full file in GitHub)

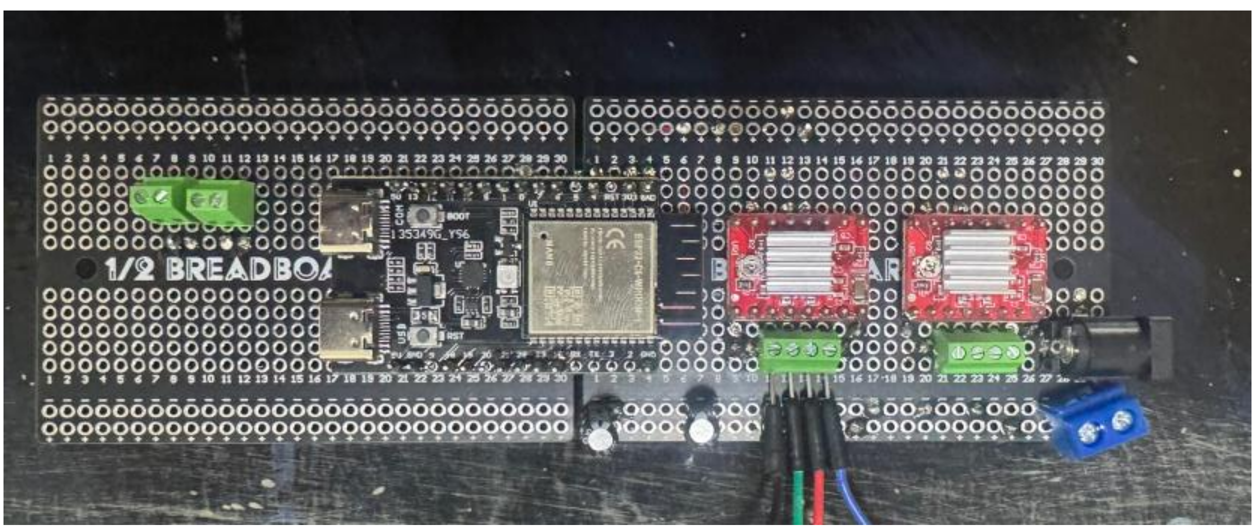


Figure 58: ESP32 Based Motor Controller Board

Budget Appendix

Category	**Item Description**	**Part Number / Link**	**Quantity**	**Unit Cost (USD)**	**Subtotal (USD)**
Linear Motion	Prototype Linear Actuator	B085SXDS2B	1	73.80	73.80
Structural Materials	Multipurpose 6061 Aluminum Bar	8975K237	1	17.64	17.64
Structural Materials	Linear Motion Shaft	1031K12	1	16.61	16.61
EDS Mounting Prototypes	PTFE-Coated Fiberglass	87865K44	1 (1ft)	34.33	34.33
EDS Mounting Prototypes	HDPE Mesh Fabric	88275K43-88275K431	1 (1ft)	9.63	9.63
EDS Mounting Prototypes	HDPE Mesh Fabric	88275K39-88275K391	1 (1ft)	6.01	6.01
EDS Mounting Prototypes	Stainless Steel	85385T28	1 (1ft)	20.62	20.62
EDS Mounting Prototypes	Stainless Steel	85385T24-85385T813	1 (1ft)	16.97	16.97
Electronics and Wiring	ESP32 Microcontroller	ESP32-C6	1	18.99	18.99
Electronics and Wiring	Motor Driver	A4988	1	13.99	13.99
TOTAL COST					$228.59