HOMES

Habitat Orientable & Modular Electrodynamic Shield

The California Institute of Technology
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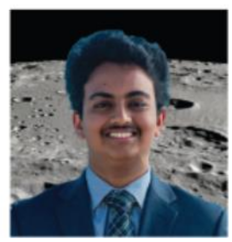
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California Institute of Technology
Habitat Orientable and Modular Electrodynamic Shield (HOMES)

Concept Synopsis

HOMES leverages and expands upon electrodynamic dust shielding (EDS) technology to mitigate lunar dust intruding into habitable spaces. Using multiple modular panels, HOMES can be tiled to actively clean floors, workspaces, walls, and other surfaces within lunar habitats.

The EDS system within HOMES is a series of 4-phase wire electrodes that generate a traveling electric field wave to locomote dust particles. The panels are rotationally symmetric and can be oriented and tiled to move dust in any desired direction.

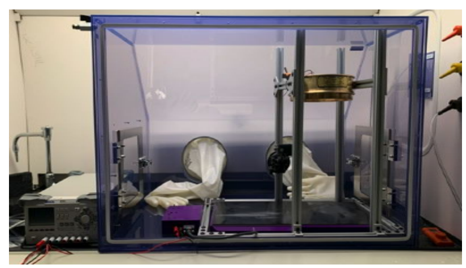
HOMES is the first and largest implementation of EDS technology that is scalable, modular, and robust enough to support an astronaut's weight. HOMES's portability, low power requirement, and long-term durability make it ideal for cleaning habitable volumes, enabling extended human presence on the moon.

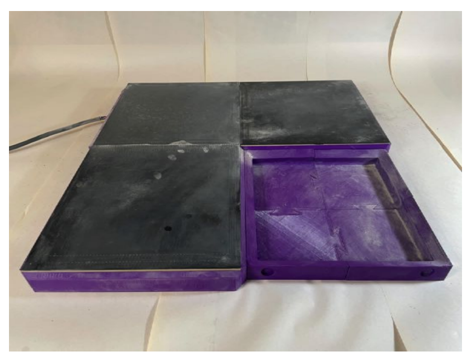
Component	Mass	Power
Panel	2.096 kg	7 W / panel
Electronics Box	0.259 kg	1.4 W

Innovations

- HOMES advances the state of the art of EDS technology and cleans interior surfaces, which helps prevent dust from making it back to Gateway and Orion when the lander returns to lunar orbit
- **Modularity:** First implementation of a modular EDS, increasing flexibility and enabling creation of interlockable enclosures to protect systems on the lunar surface
- **Scalability:** Panels can continue being added and tiled together, enabling the clearing of dust from larger areas or systems (e.g. entire interior surfaces of habitat)
- **Orientability:** Dust can be moved in any desired direction, coupled with collection panels this enables easy disposal and control of dust along any surface
- **Robustness:** Load-bearing EDS can be used in strenuous scenarios such as the habitat floor or lunar robotic systems
- **Ease of use / Portability:** No tools required for assembly, easy dust disposal through collection panel

Verification Testing Results & Conclusions





- HOMES has been rigorously tested to TRL 5 in a relevant habitat environment
- **Dust Removal:** Removes 96.91% of dust between 0.45 – 50 μm and 98.91% of dust between 0.45 – 560 μm
- **Modularity Demonstration:** Successful dust removal using four connected HOMES panels
- **Long Lifetime:** Currently undergoing long term effectiveness testing with promising preliminary results
- **Astronaut-Ready:** Load and impact tested to withstand the weight of an astronaut walking on HOMES
- **Vibration Tested:** Vibration tested to minimum NASA workmanship standards

Contents

I. Executive Summary

As humans seek to establish permanent habitats on the moon, lunar dust is one of the largest obstacles to a sustained lunar presence. Anything taken on to the moon's surface inevitably tracks dust back into habitats. Astronauts on the Apollo missions experienced issues with adverse health effects, mechanical failure, electrical failure, thermal failure, and optical failure due to dust adhesion and abrasion after its ingress in the lunar lander. The prolonged inhalation of these lunar dust particles will cause chronic respiratory problems as well as other unforeseen adverse effects [1]. The constant ingress of dust will reduce the lifetime of critical life support systems. If this is not addressed, the dust can coat floors and flat surfaces and continue to cause damage as it builds up. In addition to their other tasks, astronauts must be able to quickly clean large areas of habitable volumes in a variety of applications to prevent the build-up of dust. A successful Artemis mission should allow astronauts to prioritize scientific, exploratory, and infrastructural goals over having to fight an ongoing battle with lunar dust.

To address the gap in dust mitigation, the Caltech team introduces a unique design of scalable and modular Electrodynamic Dust Shielding (EDS) tiles. To prevent the buildup of dust on flat surfaces, the Habitat Orientable and Modular Electrodynamic Shield (HOMES) uses periodic electric waves to move dust and consolidate it for easy disposal. HOMES is a scalable modular system with rotationally symmetric panels that can be tiled to fit a desired use case. The EDS system within HOMES is a series of 4-phase wire electrodes that induce a traveling wave-like electric field to move dust particles. The panels can be rotated to move dust in any direction. For instance, HOMES can be set up on the floor of a food preparation cabin to reduce particle ingestion and consolidate the particles brought into the cabin by the astronaut.

HOMES panels are now pending a NASA Technology Readiness Level of 5 for use within the lunar habitat as it completes a rigorous testing regime. A dust locomotion test has verified that HOMES can remove at least 98% of dust particle coverage after 60 s. Each EDS panel has undergone testing of the electrical arcing and a conformal coating was proven effective against the destruction of the electronic components. The panels have also undergone mechanical load, impact, and vibration tests. These tests anticipate the maximum operable loading conditions for the panels. The load and impact tests used loads that considered the full weight of an astronaut and with added capacity, with an additional safety factor of 1.5. Furthermore, these tests were done with point loads, to maximize the stress concentration on the panel and increase the fidelity of the results. The vibration tests were done according to the Payload Vibroacoustic Test Requirement 7 in NASA-STD-7001B. The vibration test was performed to verify that HOMES could withstand the intense vibration that occurs during lift-off from the Earth's surface. HOMES passed all mechanical tests. The team has successfully demonstrated a functional modular EDS system. All that remains is the Long Term Effectiveness (LTE) testing of HOMES. LTE testing has just begun and there is an estimated year's worth of proven effective useage time for HOMES by the BIG Idea Forum.

EDS's heritage is characterized by use in small scale and specialized systems. For example, EDS has been embedded in solar panels, thermal radiators, face masks, and optical lens covers [2]. Each of these implementations are restricted to their specified use and solve problems that are well anticipated. With HOMES, we are taking EDS, a tried and true technology, and incorporating it in a scalable, modular design that will allow for tremendous flexibility in lunar dust mitigation within the context of the Artemis missions and beyond. HOMES brings EDS technology to a rugged and scalable frontier that extends beyond the scope of previous implementations. The scalability of HOMES implies that it can match the needs of any size of human presence on the moon–from initial missions to larger long-term settlements. HOMES addresses both anticipated and unanticipated gaps in lunar dust mitigation and can be made compatible with the Martian dust and environment. HOMES is a vital tool in any future lunar mission.

Fig. 1 A render of a HOMES panel with dust on the EDS

II. Problem Statement and Background

A. Challenge Addressed

NASA, in collaboration with international partners, is planning to establish a permanent lunar base of operations. A long-term mission of this sort will involve many expeditions to the lunar surface. With dust laden astronauts and equipment returning to habitats with each excursion, it is crucial that a long-term, effective solution to dust mitigation is found. As described in Section I, the jagged and charged nature of lunar dust particles offers significant risk to the function of systems and the health of astronauts. A Dust Mitigation Gap Assessment Report published by an International Working Group of space administrations across the world, including NASA, reported on the various approaches that could aid in dust mitigation [1]. According to the assessment, there are three primary methodologies with which to mitigate dust: fluidal, mechanical, and electrodynamic/electrostatic. Fluidal solutions, though potentially effective, usually depend on consumables that decrease the long-term dependency of these methods. Mechanical solutions have reduced efficacy because of the charged nature of the particles [1]. This leaves electrodynamic and electrostatic solutions as the most promising avenue for technology development to mitigate lunar dust. One such technology is electrodynamic dust shielding (EDS), which is elaborated upon in the next section. EDS is the basis of HOMES.

B. Electrodynamic Dust Shield (EDS) Technology

EDS was conceived in the 1970s as a potential solution to the many challenges presented by lunar dust. Since then, the implementation of EDS has expanded to a variety of practical applications. It is still an active area of research with regards to dust mitigation designs on lunar, martian, and terrestrial environments [3]. Typical implementations of EDS involve electrodes embedded in a surface that function as an interdigitated capacitor and create fringing electric fields above the surface. EDS systems work through lifting and transporting both charged and uncharged particles through the use of forces generated by fringing electric fields. In particle size regimes of 20 to 500 µm, Coulombic forces dominate over other forces, such as adhesive and gravitational forces [4]. Since lunar dust particles can range from 0.5 to 50 μm, an EDS can successfully remove and transport particles from this size regime.

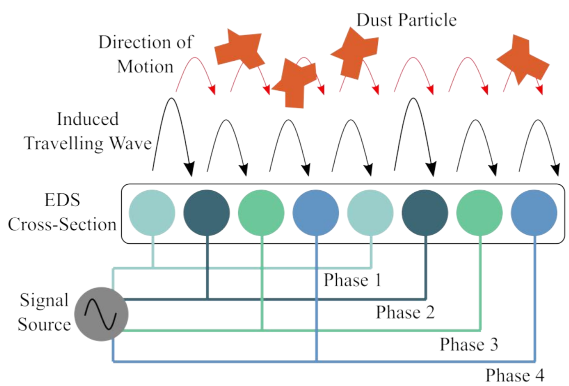


Fig. 2 Four-phase electrodynamic dust shield, adapted from [5]

EDS systems are designed to work on small scale particles [6]. In earth's atmosphere, Guo *et al.* showed that EDS can clear up to 90% of dust from solar panels, on timescales of around 30 seconds [7]. Similar experiments were conducted using a lunar dust simulant, JSC-1A, where 20 mg of dust was deposited on solar panels with various electrode configurations. The solar panels operated at 20% capacity of the panel's original output voltage without any dust mitigation, but after two minutes of EDS activation, the capacity returned to 90%. After 30 minutes, the capacity of the solar panels reached 98% of the original voltage output [8]. EDS has also been tested in various reduced gravity and vacuum environments. For instance, experiments have been conducted in high-vacuum and at lunar gravity using NASA's Reduced Gravity Flight aircraft. These experiments were conducted with various particle size regimes, from 10 µm up to 450 µm, using lunar dust samples from Apollo 16. The results of these experiments proved successful, offering a promising outlook on the efficacy of dust shielding technology in the lunar environment [9]. EDS has been deployed on the International Space Station as a part of the ongoing MISSE-11 payload to understand the performance of EDS in a vacuum environment [6]. The extensive experimentation conducted with EDS has brought the base technology to Technology Readiness Level (TRL) 8 [10]. Therefore, EDS offers an effective solution for dust mitigation. However, EDS has yet to be implemented in a modular and rugged package that would allow for expanded use cases, scalability, and versatility. The proven efficacy of EDS shows that this new avenue of implementation could have substantial success.

Most EDS systems employ a linear geometry with the electrodes having varying voltages to generate electric fields. The sets of electrodes within an EDS system usually have two, three, or four distinct voltages. With two voltages, a standing wave electric field is created. However, employing three or more distinct periodic voltages generates a moving electric field that can push particles in certain directions, as seen in [5].

EDS makes use of electrostatic and dielectrophoretic forces to attract and transport particles. The electrostatic force is exerted on already charged dust particles. The dielectrophoretic force creates a dipole moment on insulating particles and can be exerted on any particle regardless of charge. In order for an EDS system to effectively clean and remove a significant portion of the dust particles from a surface, it must overcome the Van der Waals adhesive forces and the static image charge forces. Thus an EDS system must be designed and optimized with these forces in mind. Extensive validation of the appropriate physical dimensions, electrical parameters, and overall EDS design is described in Section IV.B, alongside experimental evidence of the configuration's efficacy. Verification of HOMES has shown that it is effective at clearing surfaces of lunar dust simulants as described in Section XIII.J.3.

C. Adaptation and Integration into NASA's Planned Lunar Architecture

NASA's plan for a sustained presence on the Moon as part of the Artemis mission prioritizes the development of scientific and economic activity. Lunar dust poses a significant obstacle to these goals, as it damages equipment and endangers the health and safety of the astronauts. The highly dynamic goals of the planned lunar architecture, alongside the ubiquitous threat of lunar dust, necessitates an adaptable solution. The ease of creating any planar permutation of HOMES panels allows the technology to address both predicted and unforeseen issues. HOMES technology integrates itself within the lunar architecture and the goals of the Artemis mission due to the control, simplicity, and convenience it grants astronauts in managing dust on work benches, table-tops, and flooring. The panels are 10" × 10" × 1", about the size of a dinner plate, so it can comfortably tile on a variety of surfaces. Any surface within a lunar habitat that may regularly needed to be cleared of dust is compatible with HOMES. HOMES can repeatedly clean surfaces without wear on mechanical parts, preventing the build-up of dust and preparing areas within the habitable volume for immediate use.

Fig. 3 A 9 x 4 HOMES panel array with two collection panels in a lunar habitat hallway mudroom

While HOMES reaches to address the ever changing needs of a long-term lunar presence, HOMES also works within the constraints of the lunar architecture. Each panel is outfitted with a step-up converter, which allows the 28 V input from the lunar habitat power to be converted to the 3.8 kV needed to generate effective electric fields. The PEEK material used for the structure of the panels is strong, electrically compatible, and tolerant to a large temperature range. In fact, while HOMES is only tested for non-airlock environments, the panels only need an added thermal system to be used in the airlock. However, the thermal environment in the airlock was not sufficiently well-defined to design within its constraints. HOMES is also unobstructive to other equipment in the lunar habitat. HOMES's stackable profile makes for easy storage and transport and it's magnetic connection system allows for astronauts to quickly and efficiently change layouts.

HOMES is a scalable and modular technology that is invaluable to the day-to-day activities of astronauts. It was conceived and designed with the needs of astronauts and the constraints of the lunar architecture in mind. HOMES will play an integral role in the suite of tools astronauts of the Artemis III mission will use to mitigate lunar dust.

III. Project Description

A. Life Cycle

The HOMES team is structured based on the Agile method of project management hybridized with traditional NASA project management. This combination was able to stimulate fast decisions in addition to providing a framework to regularly review designs, thus ensuring the rapid achievement of NASA TRL 5. The entire development of HOMES is centered around the functional and design requirements described in 1, 3, and 5.

To promote constant refinement and progress, the entire project timeline is roughly split into four sprints of designing, manufacturing and testing. Each sprint culminates in an appropriate design or testing review held either internally or with Caltech and JPL faculty. The aim of each cycle is to advance HOMES by one Technology Readiness Level. The team has completed a Concept Design Review (CoDR), Preliminary Design Review (PDR), Manufacturing and Testing Readiness Reviews (MRR and TRR respectively), and will undergo a System Acceptance Review (SAR) before the BIG Idea Forum.

The first sprint encompassed the proposal writing process and early design development. The following sprint of the project commenced upon the notification of our BIG Idea Challenge Finalists status and was directed towards generating an initial proof-of-concept EDS prototype, referred to as Revision 0. This revision was followed by the Revision 1 design that integrated mechanical and electrical subsystems into a single HOMES panel. Revision 1 was punctuated by a go-no-go program of system testing. The current state of HOMES was completed in Revision 2, after results from Revision 1 testing informed further concept and design refinements. The Revision 2 design has undergone the most extensive testing to ensure mission readiness. The preceding project life cycle is further described in the table in section X. This rigorous schedule has ensured that HOMES is consistently refined and proven capable of further development and later space-flight.

B. Concept of Operations

HOMES must be packaged within a vibration isolating material for launch to the Moon in a pressure and temperature controlled environment, most likely a habitat compartment. The square, flat and, modular nature of HOMES allows for many panels to be stacked for easy transport to the Moon.

Once a habitat has been situated on the Moon, HOMES can then be unpackaged and deployed in any desired location within a habitat (ie: mudroom, food preparation area, food storage area, dust-sensitive work bench, clean room, crew cabins, agricultural cabin, and other applications).

Using HOMES is easy and time effective. The steps for use are as follows (see also Appendix XIII.A):

1) **Launch:** HOMES is packaged and sent to the moon
2) **Configure:** The modular panels are attached on a flat surface together in the desired size and orientation
3) **Attach:**
   - One or more dust collection panels are placed on the edges of the HOMES array where dust will be directed
   - The end-caps are attached on to the exposed edges of an array of panels
   - The specialized wired end-cap is connected to the electronics box
   - Electronics box is plugged into a 28V DC wall socket
4) **On:**
   - Astronauts can then commence activity on top of HOMES, which results in the deposition of dust on the EDS surface.
   - To begin cleaning the dust, the astronaut will first turn on the system power and the EDS power with two switches located on the electronics box
5) **Use:** Once on, HOMES will remove 98.9 % of dust in 60 seconds
6) **Off:** When the activity is completed, return the switches on the electronics box back to the off position
7) **Disposal:** The dust will have been transported to the collection panels. These collection panels can then be removed and carried to a safe disposal system of lunar dust
8) **Reset:** The collection panels can be returned to the HOMES array for the next use or the entire system can be stowed for another application

HOMES has an operable lifetime of 15 years, and is being verified through on-going accelerated lifetime testing described in section XIII.J. In the event of any malfunctions, HOMES can be easily dissembled and individual panels serviced by removing the 8 bolts on the bottom plate of the device.

C. Stakeholders

HOMES provides an easily configurable system for dust mitigation in lunar habitats, useful to both NASA and private companies. With further development of thermal management and use of different materials, HOMES could be used in airlocks as well as open lunar environments outside of a habitat. The novel concept of modular and scalable EDS offers promise for many applications in space exploration and longer term human habitation. The modular EDS system can be extended to many functions that require a dust-free workspace making the technology of interest to a wide variety of organizations for space, science, and commercial use. The same technology could also be adapted for regolith on other bodies, such as Mars where dust poses a similar problem. Furthermore, the scalable dust removal technology has many potential terrestrial applications for both federal and commercial entities. Clean rooms for research and manufacturing could use the panels to keep workspaces free of dust. Similarly, highly specialized vacuum chambers must be thoroughly cleaned and could use the technology from HOMES to aid in this.

D. Technical Specifications

1. High Level Requirements

In the early concept development of HOMES, the team generated the following lists of functional requirements and design assumptions to streamline and focus the completion of HOMES. The functional requirements and assumptions for HOMES are described in Table 1 and Table 2. These include technical constraints set by the BIG Idea Challenge and self-imposed conditions that have motivated the design for HOMES.

Requirement ID	Description
FR 01	Ability to manage and mitigate abrasive lunar dust
FR 02	Able to mitigate small particles (≈ 0.5-50 μm)
FR 03	Minimal barriers to NASA adoption
FR 04	Cost-effective solutions
FR 05	Non-flammable
FR 06	Remove 98% of dust in less than 60 seconds
FR 07	Operate for a minimum 15-year lifetime inside a lunar habitat
FR 08	Operational use and simplicity
FR 09	Rotationally symmetric, modular construction

Table 1 Functional Requirements

Requirement ID	Description
FA 01	Operate inside lunar habitat in controlled temperature, atmospheric, radiation, and surface conditions
FA 02	28 VDC power supplied from habitats and landers [11]
FA 03	System assembly occurs when power is off
FA 04	Panels placed on flat horizontal surfaces
FA 05	Maximum applied quasi-static load of 441 N and dropped from no higher than 20 cm
FA 06	Maximum impact equivalent to 100 kg dropped from no higher than 20 cm in lunar gravity

Table 2 Functional Assumptions

E. Design Evolution

The most current design of HOMES has application for indoor use cases only. In the original project proposal, the application of HOMES as a possible outdoor "doormat" was suggested. The feasibility of this application is limited however due to overestimates in range of EDS. Furthermore, the rigorous material and testing requirements for validating a device to survive the harsh lunar environment would detract from the function of HOMES. Primarily, designing HOMES to function on the lunar surface would require an intensive active thermal management system. As habitat airlocks for the Artemis missions are still in the design phase, the airlock use case was disregarded as the available material and thermal constraints of a habitat airlock were insufficient to design a thermal solution in HOMES. Removing this temperature shielding material and instead reinforcing the panel ensures its strength, durability, and efficiency. The team ultimately decided to focus on the indoor use cases. HOMES acts as a first line of defense to remove the bulk amount of dust that lands on the floor or other flat horizontal surfaces of a habitat.

IV. Electrical Systems

A. Design

1. Overview

The electrical system of HOMES consists of three printed circuit boards (PCBs): an electronics box, a power supply within each panel, and an Electrodynamic Dust Shield (EDS) board that sits atop each panel. The central electronics box propagates a 4-phase digital square wave that is sent to the panels, and it also handles transitions between the operational modes of the system. Each power supply converts the digital square wave into a high-voltage (HV) square wave, and the EDS boards receive this HV signal to generate rapidly varying electric fields that locomote lunar dust. All circuits use solid-state electronics so that there are no moving parts, thus fewer points of failure (EDR 06).

The electronics box is the electrical system's first point of contact with the external power as well as the user. The box receives the habitat's 28 VDC power supply–the assumed supply voltage from a lunar base or lander (FA 02)–and ground, and it delivers these inputs to the system when the system is turned on by the "Power Switch" (Fig. 4). The 28 VDC supply is stepped down to both 5 VDC and 10 VDC, the two power inputs required to generate the HV square wave in the power supply. The 10 V is also delivered to the central microprocessor of the system–currently an Arduino–that generates a 4-phase digital square wave at a frequency of 10 Hz (EDR 01, see Table 3 for information on Electrical Design Requirements) whenever the system is on. These 4 digital signals, 5 VDC, 10 VDC, and ground are outputs of the electronics box transmitted to connected power supply boards (EDR 02). The initial 28 V power supply is also needed to reach the high voltage in the power supply boards, which should only be on when necessary. Thus, there is an additional "High Voltage Switch" that should only be on (i.e. delivering 28 V to the power supply) when the user intends to use HV EDS (Fig. 4).

The power supply receives the four digital signals (Sig1 – Sig4) from the electronics box and converts each signal to a HV version of the signal (EDR 01). These four HV signals are delivered to four electrodes embedded in the EDS PCB connected directly to every power supply board (EDR 05).

It is important to note that the individual power supply feature in each panel is key to modularity of HOMES. Each power supply board has a distribution network such that it can transmit and receive the 8 outputs on any of the four sides of the square panel, so each board is connected to and communicates with up to four neighboring boards. In this way, HOMES can scale to cover as large a space as needed for dust removal.

The modularity of HOMES is enabled using spring-loaded pin connectors. These connectors were chosen for their resilience to mechanical shock and vibration that may come with operation of HOMES. Spring-loaded pins provide a low voltage, low impedance connection while being compact and easy to use. In addition, spring-loaded pins have a long lifetime (FR 07). One set of male and female eight-pinned connectors are used on each edge of the panel to facilitate rotational symmetry (EDR 05). Connector outputs include 5 VDC, 10 VDC, and 28 VDC potentials, GND, and four signals (EDR 02).

The EDS board is most directly involved in dust removal. The 4-phase HV square waves generate the nonuniform fields that are capable of removing dust efficiently across the surface of the panel. Once removed from one panel, a neighbouring panel can then redirect incoming dust to another direction so as to gather the dust in one site. Once accumulated in this location, the dust can be removed by the user or some automated system.

Together, electronics systems enable HOMES mitigate lunar dust using a simple 28VDC electrical connection from the lunar habitat. These subsystems will be described in further detail in the remainder of this section.

Requirement ID	Description
EDR 01	Ability to generate 10 Hz, 1-6 kV, four phased square waves
EDR 02	28, 10, 5 VDC, four timing signals and ground shared between all panels
EDR 03	Each of the EDS panels must have a number of electrodes divisible by four and have a 1mm pitch
EDR 04	Arcing mitigated through sufficient spacing of traces and use of dielectric materials
EDR 05	Only one required connection from panel array to electronics box
EDR 06	Solid-state circuit

Table 3 Electrical Design Requirements

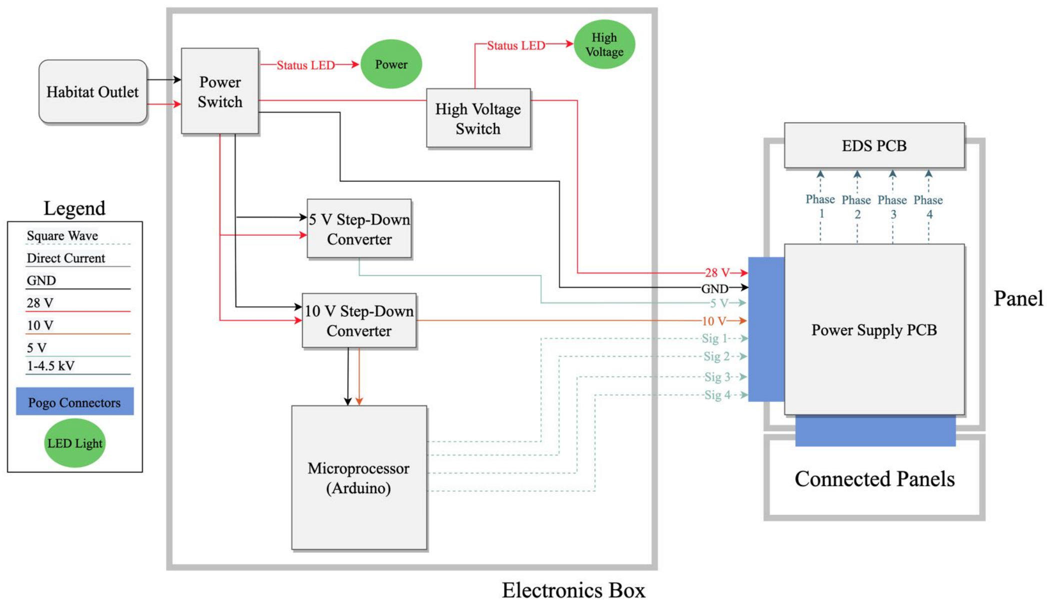


Fig. 4 Electrical system block diagram

Electronics Box	Power Draw: 1.4 W Voltage: 28 V Current: 0.05 A
One panel	Power Draw: 7.56 W Voltage: 28 V Current: 0.27 A
Two panels	Power Draw: 13.72 W Voltage: 28 V Current: 0.49 A

Table 4 Electrical Characteristics of Electronics Box and Connected Panels

2. Electrodynamic Dust Shield

A robust four phased interdigitated capacitor is essential to the electrodynamic dust shielding technology (EDS) of HOMES. To generate dielectrophoretic and Coulombic forces to transport dust, four 3.8 kV square waves, each 90 degrees out of phase, are applied to the EDS electrodes (EDR 01). Even with high voltage, the effective range of EDS is less than 0.5mm, thereby requiring the EDS electrodes to be directly on the top surface of HOMES. To allow for the seamless transport of dust from one panel to another, the EDS electrodes must span the entire top area of each panel. Each panel is approximately $10\,in \times 10\,in$ to easily tile a large surface, be small enough to handle with one hand, and provide sufficient area and volume for the enclosed EDS power supply circuitry. To further facilitate the seamless transport of lunar dust, the number of EDS electrodes must be divisible by four to ensure dust can be continuously lifted across adjacent panels (FR 09, EDR 03). Literature reviews of previous EDS implementations concluded that a 1 mm electrode pitch and 0.25 mm electrode width would best transport lunar dust in the targeted regime of $0.5 - 50\,\mu m$ (FR 2). Given the divisibility and pitch constraints for the EDS electrodes, the top surface of HOMES is 256 mm or 10.079 in in length as well as in width. This corresponds to panels of 256 electrodes each, all electrodes interconnected in repeating sets of the four phases.

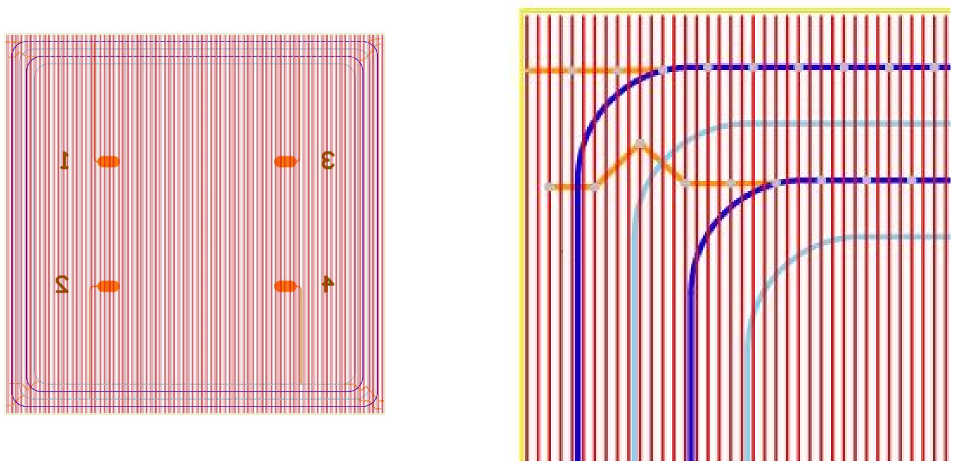


Fig. 5 EDS PCB computer-aided design (CAD) (full view on left, upper-left corner close-up on right). For this 4-layer board, each color represents its own layer: the electrodes are in red, HV power distribution loops for phases 1 and 3 in dark blue, power distribution loops for phases 2 and 4 in light blue, and additional HV power routings in orange.

The EDS electrodes on HOMES are constructed out of a rigid four layer PCB (see Appendix Section XIII.H). Manufacturing an FR4 rigid EDS PCB allowed for inexpensive and rapidly manufactured prototypes (FR 04). While flexible PCBs were considered due to their stronger dielectric properties compared to FR4, they were ultimately eliminated due to their manufacturing complexity, high cost, and the arcing failure of multiple prototypes. Although the EDS PCB cannot be the sole load bearing surface on the top of HOMES, a rigid PCB does add flexural strength and impact resistance in addition to the PEEK supporting plate described in Section V.D.1. To utilize the maximum electrode coverage on the surface the EDS PCB, a four layer PCB stack-up was chosen. This allows the top layer to contain all electrodes while the other three layers can be used for routing and power distribution. The traces in the bottom three layers are spaced apart as much as possible to reduce the risk of arcing and cross-talk. The EDS PCB is connected to the EDS power supply via solder pads on the bottom of the board.

High potential testing of EDS PCBs early in the design process concluded that high dielectric strength conformal coating is the best solution for preventing arcing on the top (EDR 04). The conformal coating does not set with air bubbles or cavities that could cause arcing. Adhesive dielectric film applied over a large surface area is susceptible to multiple air cavities which allow for arcing. On the underside of the EDS PCB, Kapton is used to prevent arcing around small regions of vias, as it is much easier to remove air bubbles from taped regions. The conformal coating does have the significant disadvantage that it has a very low abrasion resistance. Potential solutions for this issue are addressed in Section VIII.A.

It was observed that the larger 10 in by 10 in Revision 2 EDS PCBs had significant voltage drops when charging, a quarter period after turning on (see Figure 6). Compared to our original 5.5 in by 5.5 Revision 1 EDS PCBs, this phenomenon was not observed. An oscilloscope and capacitance meter were used to determine this effect is caused by parasitic capacitance between adjacent phases. LTSpice simulations of coupled capacitances between electrodes showed the same result. However, the effect is negligible for the panel's ability to move dust.

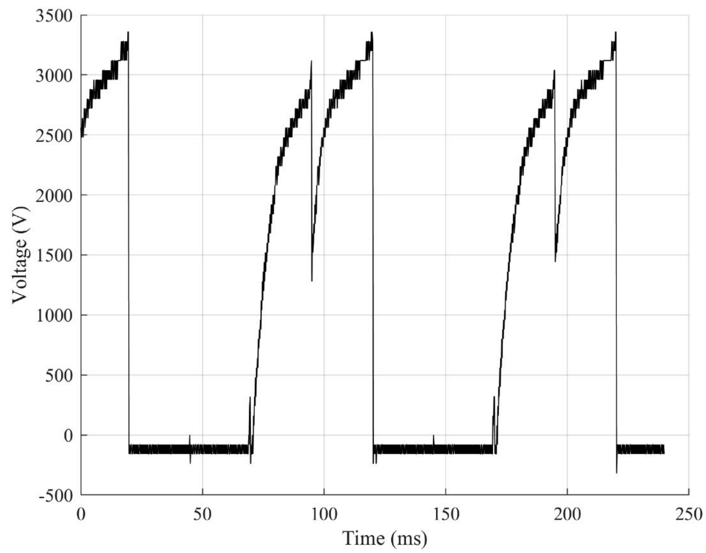


Fig. 6 Oscilloscope measurement of the high voltage square wave in a 10in x 10in EDS PCB. There is clearly a voltage drop at the beginning of each corresponding digital "on" signal sent by the arduino to the power supply

3. Panel Power Supply

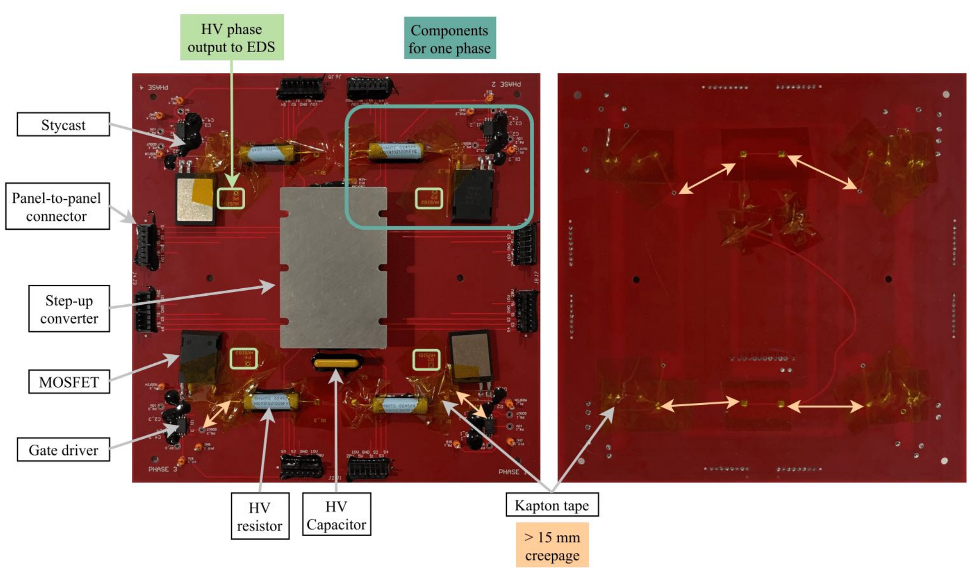


Fig. 7 Power Supply PCB 8in x 8in (front view on left, back view on right). See Appendix Section XIII.G

EDS requires HV square waves across electrodes to generate the periodic electric field gradient required to transport insulated dust particles. We chose a four phased EDS approach as it provides a more continuous driving electrodynamic force and aids in the rotational symmetry of our design. These square waves oscillate at a amplitude of 1-4 kV and a (relatively low) frequency of 10 Hz (EDR 01). Furthermore, each of the four square waves are equally out of phase by 90°. These specifications are supported by literature, experimental, and computational evidence. To effectively move dust, existing research suggests that HV square waves must have rise and fall times between 10 - 100s of nanoseconds [8]. These specifications constrain the power supply housed within each panel. The team designed a Metal Oxide Semiconductor Field Effect Transistor (MOSFET) switch circuit (see Appendix Section XIII.G.1) to generate the described waveform for EDS. A half-bridge circuit can satisfy the same electrical requirements as the MOSFET switch circuit with lower power. Unfortunately, there are no readily available gate drivers with a sufficient isolation voltage (needed to be in excess of 3000 V) to support the electrical constraints.

In each Revision 2 HOMES panel, a high voltage DC-DC converter transforms a 28 V input into a 3.8 kV output. A ceramic capacitor is placed across the high voltage terminals of the DC-DC converter to filter high frequency noise. The filtered 3.8 kV output powers MOSFET circuits which allow for the switching of high and low potential across the EDS electrodes, thus creating square waves. The timing for this switching is controlled by a 5 V square wave from a micro-controller. Gate drivers are used to augment the signal to be powerful enough to drive the MOSFETs. Four of these MOSFET switching circuits are connected to one high voltage DC-DC converter to output the four phased EDS waveform (see Appendix Section XIII.G.1). When the MOSFET is off, the electrodes charge slowly through a high power resistor. When the MOSFET is on, the electrodes discharge to ground, providing a fast fall time.

These components were implemented on a four-layer power supply Printed Circuit Board (Fig. 7) that fits inside a HOMES panel. The largest concern of the Revision 2 EDS power supply PCB was the potential for arcing and subsequent destruction of components. This change was motivated by continual arcing issues with the smaller power supply PCB of the HOMES Revision 1. The improved four-layer PCB complies with Institute of Printed Circuits (IPC) 2221 minimum creepage distance for 3.8 kV external component terminations to mitigate the risk of arcing. The length of wire harnesses was minimized by placing loops of traces around the perimeter of the PCB for every signal. Each power supply board had Kapton tape placed on all high voltage traces and leads. These measures were implemented to prevent inadvertent contact of conductors to high voltage, which could destroy the PCB. Finally, NASA's high voltage soldering terminations standards allowed for effective coronal effect prevention at wire terminations and other connections. [12]

For structural integrity–specifically vibrational robustness–Loctite Stycast has been applied to the most at-risk components, which include the small surface-mount capacitors and gate drivers. (see figure 7)

4. Electronics Box

Each panel needs 28 V, 10 V, and 5 V power sources, along with 4 square wave timing signals from a micro-controller. The electronics box uses DC-DC converters to create the 5 V and 10 V potentials. The 5 V and 10 V potentials supply the gate drivers in each panel. The 10 V potential is also passed through the micro-controller to generate a synchronous set of wave signals for a panel configuration. The 28 V potential is channeled to panels to be individually stepped up in each power supply PCB. (see Appendix Section XIII.F)

The electronics box is an singular external system that provides each power supply PCB in a HOMES panel with the necessary voltages and signal(EDR 05). The entirety of HOMES is supplied power from the habitat through a cable that connects an outlet to the electronics box. The eight signals generated by the electronics box are directed through a D-sub cord into a specially modified end-cap that interfaces with a HOMES panel (see Appendix Section XIII.F.4). The modular construction of each panel then allows for these eight signals to be shared across an entire array. The electronics box is intended to supply as many panels as is needed.

The electronics box has a simple user interface consisting of two switches and LEDs. One switch supplies power to the entirety of the electronics box, while the other turns on the dust moving action of HOMES. There is a red LED that displays the state of each switch respectively. (see Appendix XIII.F for schematics and CAD)

5. Software

HOMES is controlled by a software consisting of a simple code program implemented with an Arduino UNO R3. This code, written in the Arduino IDE, turns on and off 4 digital signals (i.e. writes them high or low) to generate the four desired digital square waves at a frequency of 10 Hz.

The 4 digital signals are assigned to digital pins on the Arduino and function as outputs of the microcontroller that are delivered to the electronics box and, from there, to the power supply panels and the rest of the system. Whenever the power switch in the electronics box is turned on, the Arduino is on and receiving 10 V of power, so it is generating the 4-phase square wave. (see figure 8)

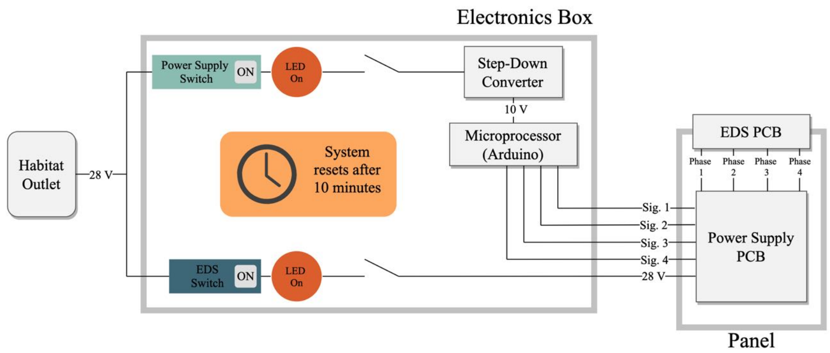


Fig. 8 Software block diagram .

B. Validation

1. Optimal Voltage and Frequency

A functioning EDS system relies on consistent AC frequencies and voltages driving the EDS in order to effectively transport dust. The optimization of the frequency and voltage parameters is constrained by power usage concerns and technical limits. COMSOL Multiphysics was used to determine the ideal voltage and frequency parameters with which to drive the EDS PCB and maximize the force exerted on dust particles.

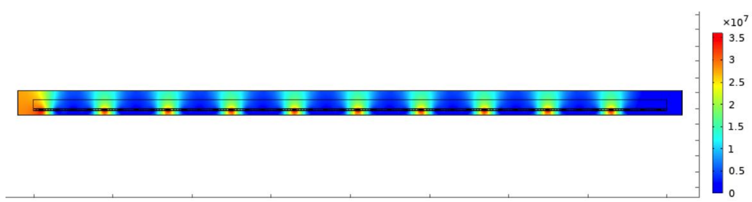


Fig. 9 Two-dimensional cross-section of EDS panel in COMSOL software

A two-dimensional cross-section of the panel was created in the COMSOL environment. This schematic, as seen in Fig 9, assumes that there is no electric field gradient along the direction parallel to the wire electrodes. This two-dimensional cross-section can be used to determine the electric field gradient and potential in the direction perpendicular to the wire electrodes–the intended direction for dust to travel. The potential is a key input in determining the total amount of force across the EDS panel. The following equation represents a force balance between the induced electrodynamic forces and dielectrophoretic forces, and the opposing adhesive and gravitational forces acting on the dust particles. The "es.normE" represents the amplitude of the electric field.

$$3.9 \times 10^{-14} \times es.normE + 2\pi \times (8.85 \times 10^{-12}) \times \frac{3.1-1}{3.1+2}\left(\frac{0.00005}{2}\right)^3 \times (d((es.normE)^2, x) + d((es.normE)^2, y))$$

The frequency-voltage space was constrained to ranges of 0-30 Hz and 2-6 kV. Across this space, the electrical potential of the 2D panel cross-section was calculated and inputted into the force balance equation.

The simulations found that force increased monotonically with voltage, and thus a voltage of 6000 V was the most effective. However, constraints on components and physical limitations brings this optimized value down to 3000 kV.

Frequency was found to have no effect on the force exerted on particles, so a value of 10 Hz was adopted. There was less priority on determining a precise optimal frequency, since it can be easily modulated via the micro-controller.

C. Benchtop Testing

1. Overview

Bench top testing provided essential design verification as HOMES evolved and provided the framework for TRL 4 testing. The bench top testing facilitates rapid, iterative, design changes. All revisions of HOMES have undergone some extent of bench top testing, with the recent Revision 2 having passed a complete bench top verification regime. Bench top testing progressed alongside technological complexity. In order, these tests include singular panel EDS effectiveness testing, power supply functionality tests, power supply and EDS mating tests, modularity testing, and electronics box testing. EDS effectiveness testing and power supply functionality tests occur concurrently, to streamline their integration. The results of these tests both motivated the changes and ensured readiness of Revision 2 to continue to high fidelity testing.

Fig. 10 Successive stills of dust being removed from a single HOMES panel. $\Delta t \approx 1.5s$

2. Single Panel Testing: EDS

The single panel EDS tests aimed to characterize the performance of the EDS, both in its durability and ability to move dust. A high potential (HiPOT) tester was used to determine the electrical breakdown voltage of the EDS board prototypes. The boards were coated with varying levels of dielectric protection: only Kapton, only conformal coating, both, and neither. Starting at 1 kV, we incremented the voltage going into the board by 1 kV, up to 5 kV. Tests were recorded to capture any arcing events, which were observed in the form of visible sparks and crackling noises as well as sharp drops on the oscilloscope reading. An optical microscope was also used to investigate locations of arcing

Boards without any form of dielectric protection arced at around 2 kV, while boards with only a thin layer of conformal coating arced around 3 kV. However, once Kapton was added to the board, independent of the conformal coating, the EDS panel reached 5 kV without arcing.

These tests set a team standard for how to mitigate arcing on small boards. Either dielectric material needs to cover HV leads or HV components must be placed a minimum distance away from low-voltage leads. Thus, for all subsequent tests on boards in which the minimum distance was not met, Kapton tape covered HV leads and nearby low-voltage and ground leads. However, applying the Kapton onto the large surface area of the EDS PCBs frequently created air bubbles and left PCBs vulnerable to arcing. To address this, the current design appropriately spaces high voltage leads and utilizes a thick layer of conformal coating on the EDS to negate the risk of arcing. (see Appendix figure 34)

3. Power Supply Functionality Tests

We tested the EDS power supply by powering the board with a bench top power supply that provided the 28 V, 10 V, and 5 V power. The circuit board was also connected to an Arduino microcontroller. To minimize the risk of damaging components if a fault was found, we first tested each circuit at a low voltage which would then be followed by the operating high voltage. Using an oscilloscope, the resulting HV signals for each phase were observed (see figure 6). Testing Versions 2 and 3 of the power supply involved observing the behavior of the system with (i) only low-voltage power and (ii) both low- and HV signals.

(i) Low-voltage testing: The tests focused on verifying the low-voltage signal output. The gate drivers were isolated by disconnecting the MOSFETs. The Arduino was then connected to the board, and a benchtop power supply powered the gate driver. To monitor the signals, each phase was probed and validated for the square wave output from the gate driver, which is also the MOSFET input (see figure 11). Key signal characteristics validated included the square wave period, duty cycle, magnitude of the voltage output, and signal consistency with time. Physical characteristics monitored for included overheating (measured with a laser heat sensor) and visible sparks indicating arcing. Once each phase was validated, the MOSFETs were added. The benchtop power supply powered 10 V to the high side instead of the high voltage signal, the $1M\Omega$ resistor was replaced with a $10k\Omega$ resistor to allow for measurements of the MOSFET drain output. Once the electrical characteristics were verified, HV testing proceeded.

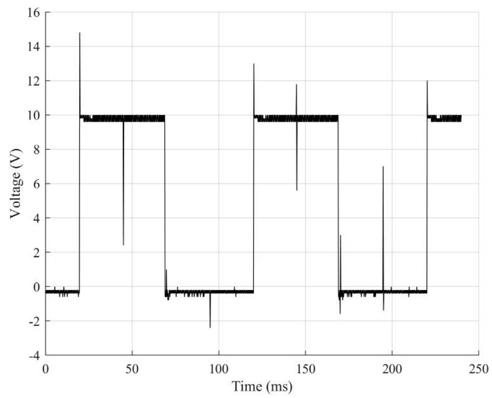


Fig. 11 Digital Signal Measured at the MOSFET Input During Low Voltage Testing

(ii) HV testing: These tests observed the behavior of a fully assembled board receiving both low voltage and high voltage signals and power. We connected the board to the Arduino as well as the benchtop supply providing the 28 V, 10 V, and 5 V power. Similar to the low-voltage tests, an oscilloscope was used to read both the low-voltage gate driver output and the HV output for each phase. The same electrical characteristics were validated again. (see figure 6)

4. Power Supply and EDS Mating

All three versions followed similar procedures for functionality testing. HV-rated wires were soldered from the power supply to the Kapton-covered EDS board. As in prior tests, the desired waveforms and the absence of arcing were verified on both the power supply and EDS boards. One important observation is that each panel draws 6.1 W of power.

The primary purpose of the mating tests was to test the mobility of dust on one panel, which consisted of a power supply board connected to a benchtop power supply and an EDS board. In initial tests, dust was arbitrarily poured into the middle of the panel, which created clumps. This setup was not a realistic representation of the distribution of dust on a panel, however, so subsequent tests were configured to have a constant mass of dust simulant evenly sieved across the EDS board. This process also ensured that the simulant was electrically charged to better replicate real properties of lunar dust. The board's success in clearing the dust was measured through visually inspecting a video recording of the test run (see figure 10). This analysis proved to be sufficient in evaluating efficiency.

5. Modularity Testing

The setup for the mating tests was replicated, and additional power supply and EDS pairs were connected (each power supply and EDS pair had been tested individually before these tests). Trials with two, three, and four panels connected to each other used the previously described dusting distribution procedure to observe the panels' efficiency at locomoting dust. For each set of panels, different configurations of EDS board orientations were set up to check the ability of the panels to, for example, turn dust around a corner.

6. Electronics Box Testing

Testing the electronics box PCB was straightforward. We connected the electronics board to the benchtop power supply and the Arduino. (see Appendix Section XIII.F.4) Version 1 proved to have some minor routing issues that were easily adjusted in Version 2. One major change was switching the linear regulator with a step-down converter, since we observed that the linear regulator dissipated too much heat within the tens of seconds for which it was on. (see Appendix Section XIII.F)

V. Mechanical Systems

A. Panel Design

HOMES was designed with the objective of being a practical and easy to use dust mitigation system. HOMES consists of multiple rigid EDS-embedded panels that can be attached to a maximum of four other panels in any planar orientation (FA 04). This allows for many different configurations and field directions. Each HOMES system consists of 4 rigid panels, 1 electronics box, 10 endcaps, and 1 collection panel. The EDS is embedded within the panels. The electronics box provides the system with power. The panels are first assembled in the desired configuration and then connected to the electronics box, from which the entire system receives power. Table 5 outlines the technical requirements that motivated the mechanical design of HOMES.

Requirement ID	Description
MDR 01	Support launch and landing loads during transport
MDR 02	Support weight of astronaut (441.045 N) on a single panel in lunar gravity
MDR 03	Structural materials have a high dielectric constant
MDR 04	All selected materials have similar coefficient of thermal expansion

Table 5 Mechanical Design Requirements

Each HOMES panel is a 25.6 cm by 25.6 cm square to optimize for surface area and modularity while minimizing internal bending moments (MDR 02). An exploded view of an individual HOMES panel is depicted in Fig. 12. The structural housing of HOMES consists of four separate PEEK sidewalls, a PEEK top sheet, and an aluminum bottom plate (FA 01). The side walls are attached to form a central cavity which houses the power circuitry. The dimensions of the side wall, 2.81 cm tall and 2 cm wide, support loads and shield the power circuitry from the environment. Each sidewall has a flat outer surface, with 45º chamfers at the corners to provide for seamless alignment when assembled. The side walls are connected with screws. There are also holes cut out for wire routing and electrical connections. A 25.6 cm by 25.6 cm by 0.3 cm PEEK plate lays on top of the sidewalls and supports the EDS electrode circuit. A 25.6 cm by 25.6 cm by 0.2 cm aluminum bottom plate lies under the side walls. This layer provides additional structural support, shielding from the outer environment, and thermal dissipation (FA 05). Structural validation is discussed in Section VI. The total mass of the structural housing of one panel is 0.942 kg (FR 03).

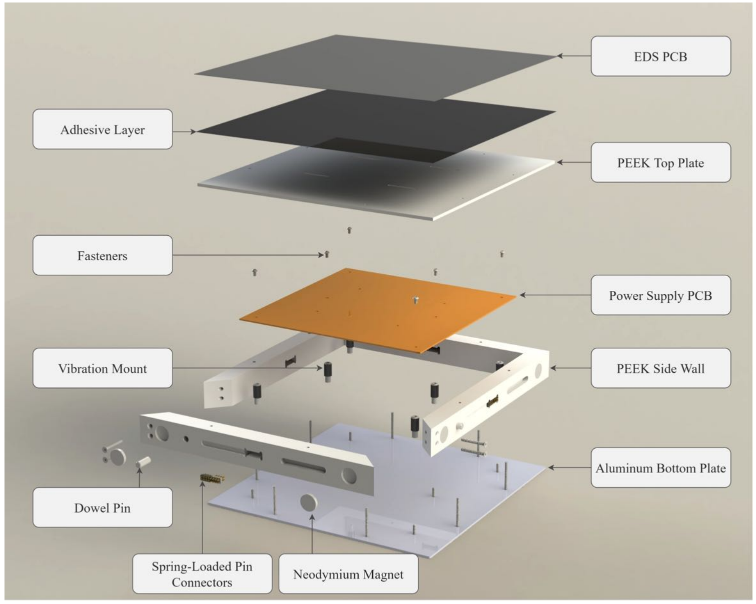


Fig. 12 Labeled exploded view of an individual HOMES panel.

Adjacent panels can be connected together by aligning edges and the spring-loaded pin connectors, alignment dowel pins, and the two 44.5 N neodymium magnets on each side of the panel. The magnets create a strong connection in the horizontal direction while the dowel pins help secure against vertical movement. This provides for a mechanical interface that is easy to attach, even with bulky spacesuit gloves (FR 08, FA 03).

To reduce the possibility of internal damage during flight, the power supply PCB was vibrationally isolated from nearly every other component of HOMES (MDR 01). This was achieved by undersizing the power supply PCB in relation to its central cavity and mounting it with vibration-damping standoffs. The separation distance between the walls of the central cavity and the power supply PCB was selected by the maximum elastic deformation of the standoffs.

Thermal management of the power supply PCB uses conduction to transfer heat from the hot DC-DC HV step-up converter through a thermal gap pad to the aluminum bottom plate. The thermal gap pad is both flexible and conductive to absorb vibrations while acting as a heat spreader.

These design features were validated by the success of the panel after extensive vibration testing, as described later in Section VI.

B. End Caps, Collection Panel, and Electronics Box

End caps are necessary to insulate the exposed electrical contacts on outer panel edges. Without insulation, charged lunar dust may stick to exposed spring-loaded pins and have unintended effects. As such, the end caps do not contain any electronics or wires. The end caps act as a physical barrier to limit the amount of dust in the joints. The end caps can be attached to any exposed edge.

A collection panel is necessary to collect the moved dust after use of HOMES. The collection panel can later be removed to dispose of the dust. This feature consists of a slanted cavity angled at 60º to accommodate for the lunar dust angle of repose [13]. The collection panel uses the same dowel pin and magnet system as the panels and can be connected to any exposed edge.

An electronics box is a separate module that can be placed on the outer perimeter of the system and can be attached to any panel via a 9-pin D-sub connector. The box itself has 2 LEDS and 2 toggle switches. The LEDs display the operational modes of HOMES: one light indicates whether the system is powered, and one light indicates when EDS is operational. The toggle switches allows for the user to change modes. One toggle switch controls the state of the power supply and the other toggle switch controls the state of the EDS, as previously described in Section IV.

C. Material Selection

The material selection was driven by the functional requirements and mechanical design requirements outlined in Tables 1 and 5 above, and by the environmental conditions that HOMES will operate in. The functional temperature range, coefficient of thermal expansion, load-bearing capabilities, and electrical insulation have been prioritized (MDR 03 and MDR 04). Additionally, all selected materials are non-flammable (FR 05). The structural side-walls and the top plate were constructed out of PEEK, which was selected due to its favorable strength and dielectric constant, and its use in other space applications, such as cubesats 3D printed out of PEEK for the ESA's QB50 mission [14]. The bottom plate was manufactured from aluminum to provide additional structural integrity, and offer a means to dissipate heat, while minimizing cost and weight.

Subsystem	Component	Material	Mass (kg)
Panel	Side wall	PEEK	0.175
	Top plate	PEEK	0.441
	Bottom plate	6061 Aluminum	0.344
	Power supply board	FR4	0.344
	EDS Board	FR4	0.203
		Panel Total	2.096
Collection Panel	Panel	PLA	.276
End Cap	Cap	PLA	.037
Electronics Box	Structural housing	PLA	.190
	Power supply board	FR4	0.069

Table 6 Subsystem material, mass, dimensions, and power summary.

D. Validation

1. Selection of PEEK

The optimal material for this layer of underlying support would be one that could minimize the capacitance of the system. A buildup of capacitance under the EDS system would negatively interfere with the electric field created by the EDS. To validate PEEK to be the optimal material for minimizing capacitance, COMSOL simulations compared PEEK against the following materials: Macor, ULE, Vespel, Kapton, and Zerodur. As seen in Fig. 13, PEEK offered the lowest capacitance at every thickness of material studied.

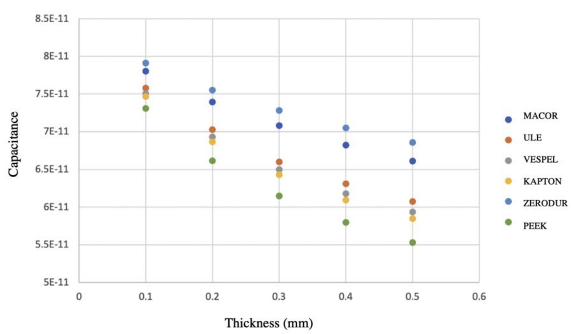


Fig. 13 Comparing capacitance of various materials at different thicknesses

2. Load Requirement

Additional validation was done to the PEEK layer to minimize its thickness without compromising its structural integrity. A thinner layer reduces weight, thus reducing launch costs. An ideal thickness was first determined using

COMSOL and then verified with SolidWorks Simulation. For the PEEK material parameters, tensile testing, as detailed in the Appendix, was conducted.

In COMSOL, a 470 N point load was added to a 25.6 x 25.6 cm PEEK plate with thicknesses varying from 0.1-0.5 cm. The load of 470 N was selected to model an extreme case of an astronaut holding a heavy load. Given these constraints, we aimed to identify a thickness that could achieve a von Mises factor of safety of 2. The determined optimal layer thickness was around 4.7 mm.

These COMSOL results were verified in SolidWorks Simulation with a design study following the same material properties and thickness range. The constraints minimized mass and set a minimum von Mises factor of safety of 2 while the simulation conditions applied a 470 N load across a 5 cm circle at the center of the plate and fixed a 2 cm "ring" around the edges opposite to the force. The design study confirmed the COMSOL findings and the layer thickness of the PEEK top plate supporting the EDS PCB was set to 4.75 mm to match vendor availability.

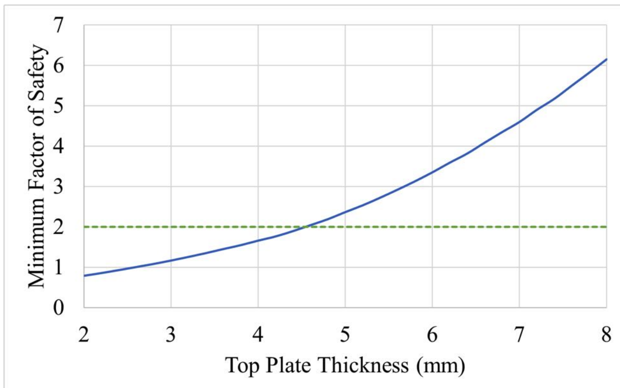


Fig. 14 Results from Solidworks Simulation to determine optimum top plate thickness.

VI. Verification

A. Requirements

The HOMES verification program has allowed HOMES to be qualified to TRL 5, which consists of component demonstration in a relevant environment. The physical survival of the panels within the chosen use-case of a dust-free work surface inside the lunar habitat has been verified by mechanical testing, including load testing to verify that the panel can sustain the load of an astronaut in lunar gravity and impact testing to ensure that a dropped object or sharp point will not cause destruction of the panel (FA 05 and FA 06). Electrical testing, including dust locomotion testing and high potential (Hipot) testing has been performed to verify panel functionality and characterize the arcing thresholds. Vibration testing was performed to ensure that the panel meets workmanship quality standards for electronic components traveling to space. Finally, long-term effectiveness testing is ongoing to verify the survival of the HOMES system for the 15-30 year lifespan given in the design guidelines. Cumulatively, these tests serve to verify the functionality of the HOMES panel system within the expected environment of a lunar habitat and demonstrate long term survival through the possible extremes of use. See Appendix XIII.J for images of our custom-built rigs to conduct these verification tests.

B. Load Testing

The mechanical load test was done to ensure HOMES can withstand astronauts standing and walking on the panels. A fully constructed HOMES panel underwent a series of ambient temperature quasi-static spherical loading tests (FA 01 and FA 05). The spherical loading consisted of a rounded point load being applied to the center of the top face of HOMES while being supported by a plate along the opposing bottom face (FA 04). The tests required precise data acquisition to determine the point of mechanical and electrical failure of HOMES. A Vishay 7000 StrainSmart Data Acquisition System with High Level and Strain Gage Input Cards allowed for the synchronous collection of load and strain data. The test was conducted at an ambient temperature of 22° C using a target load of 441.045 N. This load was calculated using 100 kg for the maximum mass of the astronaut standing on the panel and 81.5 kg for the maximum mass of items being carried by the astronaut. Using $1.62 m/s^2$ for the acceleration due to gravity on the surface of the

*All tests conducted at room temperature and pressure.	TEST NAME	DESCRIPTION	CONDITIONS	TRL	RESULTS
ELECTRICAL	*Dust Locomotion*	EDS functionality with modularity	Sieved LHS-1 onto HOMES	4	<45 μm-sized dust was moved off HOMES
	High Potential	Arcing thresholds characterization of EDS PCB	1-5 kV testing with varying levels of dielectric protection	4	Conformal coating was found to be better than Kapton for EDS PCB
	Long Term Effectiveness	Accelerated electronic lifetime test through repeated on/off cycles	Simulating 15 years of use on the Moon	5	Still in progress
MECHANICAL	*Load*	Sustained astronaut weight from a point load	Simulating standing on HOMES with pebble stuck in boot	5	Passed with 442.8 N that was sustained for 20 seconds
	Impact	Sharp impact from a point load	Simulating jumping on HOMES with pebble stuck in boot	5	Passed with a 100 kg impact from 24.7 cm in lunar gravity
	Vibration	Identification of latent defects and manufacturing flaws	Minimum workmanship random vibration test	5	Passed PVTR 7 standard in NASA-STD-7001B

Fig. 15 Testing Overview

Moon gave 294.03 N for the maximum weight of the astronaut and the items they carry. The force exerted by a person on the ground while walking is about 1.5 times their weight [15] so the maximum force exerted by an astronaut walking on HOMES would be $1.5 \cdot 294.03N = 441.045N$.

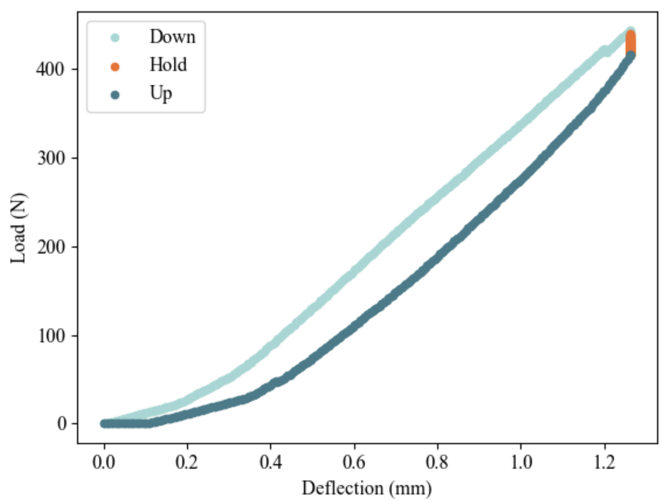


Fig. 16 Load-deflection curve of HOMES panel during uniaxial load testing

HOMES passed the load testing, retaining functionality after sustaining a load greater than the calculated load for the maximum force exerted by an astronaut walking on HOMES. During testing, a maximum load of 442.8 N was reached. Additionally, a load above 415 N was sustained for 16 seconds. After load testing was performed, the electrical functionality of the panel was tested and it was verified that the panel retained its original dust moving capability.

C. Impact Testing

The impact test was conducted to simulate a situation where a point load is applied suddenly to HOMES, such as if a rock was stuck in the boot of an astronaut while stepping on the panel, or if an object was dropped on HOMES while being used as a work surface (FA 06). To conduct this test, a rounded impactor was mounted on dual linear bearings and dropped onto the EDS PCB. After each height interval, the integrity of the panel was determined by measuring electrical continuity between traces in the area of impact.

From this testing, it was determined that integrity of the panel was maintained up to a drop height of 75 cm. Using the mass of the impactor and differences in gravity between the Earth and the Moon, it was determined that this drop height was equivalent to a 24.7 cm drop of a 100 kg astronaut on the lunar surface.

$$(0.75\text{m})(5.44\text{kg})(9.81\text{m/s}^2) = h_m(100\text{kg})(1.62\text{m/s}^2),\ h_m = 24.7\text{cm} \tag{1}$$

This indicates that the panel is capable of withstanding a point load, such as from a rock stuck in a boot from an astronaut performing at least a 24.7 cm jump. This resistance to impact should be sufficient to ensure panel survival in the defined use case of HOMES.

D. Vibration Testing

The random vibration test was conducted to ensure that HOMES meets NASA's minimum workmanship criteria for electrical, electronic, and electromechanical components weighing less than 50 kilograms. Specifically, HOMES was tested to Payload Vibroacoustic Test Requirement (PVTR) 7 in NASA Standard NASA-STD-7001B. This test can identify latent defects and manufacturing flaws in electrical, electronic, and electromechanical hardware at the component level.

A shaker table provided by Professor Sergio Pellegrino's Space Structures Laboratory at Caltech was used to conduct the test. The test was conducted using one HOMES panel and the functionality of the panel was evaluated before and after the test. The test was conducted by attaching one HOMES panel to two 6 inch by 6 inch by 12 inch square tubes made of 6061 aluminum alloy. The tubes had a ¼ inch wall thickness. The tubes were attached to the bottom of HOMES using M3 x 45 mm screws and the tubes were attached to each other and the shaker table using ¼-28 screws. The tubes were attached to the shaker table in three orthogonal orientations to test the ability of HOMES to withstand random vibration along three orthogonal axes. The random vibration specifications shown in Table 7, which is from section 4.3.3.1 of NASA-STD-7001B, was used to test HOMES. The shaker table was ran using this random vibration profile for one minute along each of the three axes. For each of the three axes, an accelerometer was placed within an inch of where HOMES was mounted to the aluminum tubes and the shaker table was modulated such that the readings from this accelerometer were as close as possible to the vibration specification in Table 7. Although the shaker table was

Frequency (Hz)	Acceleration Spectral Density (g^2/Hz)
20	0.01
20-80	+3 dB/oct
80-500	0.04
500-2000	-3 dB/oct
2000	0.01
Overall Level	6.8 g_{rms}

Table 7 Component Minimum Workmanship Random Vibration Test Levels (NASA-STD-7001-B PVTR 7)

modulated to provide acceleration spectral density levels as close as possible to the table above, in some frequency ranges, the levels were outside of the targeted specification, due to limitations of the shaker table. The random vibration levels measured by the accelerometer along each axis are shown in Fig. 17. The x and y axes were along the length and width of HOMES and the z axis was along the height of HOMES.

After the vibration test, HOMES was thoroughly inspected and no damage was found. The functionality of HOMES was also tested before and after the vibration test and it was determined that the vibration test had no effect on the functionality. Ideally, HOMES would have been tested to the qualification random vibration levels in NASA-STD-7001B, which are the maximum expected flight levels + 3dB. However, the shaker table used for the minimum workmanship test was unable to reach the acceleration spectral density levels needed for qualification testing, so the minimum workmanship test was the only random vibration test that HOMES underwent.

E. Long-Term Effectiveness Testing

The purpose of the long term effectiveness test is to verify that the electronics will be able to run for HOMES's expected lifespan of 15-30 years (FR 07). The electronics are repeatedly started up and shut down in a continuous cycle for 12 days in order to perform accelerated life testing. We are conducting this test over two fully operable HOMES

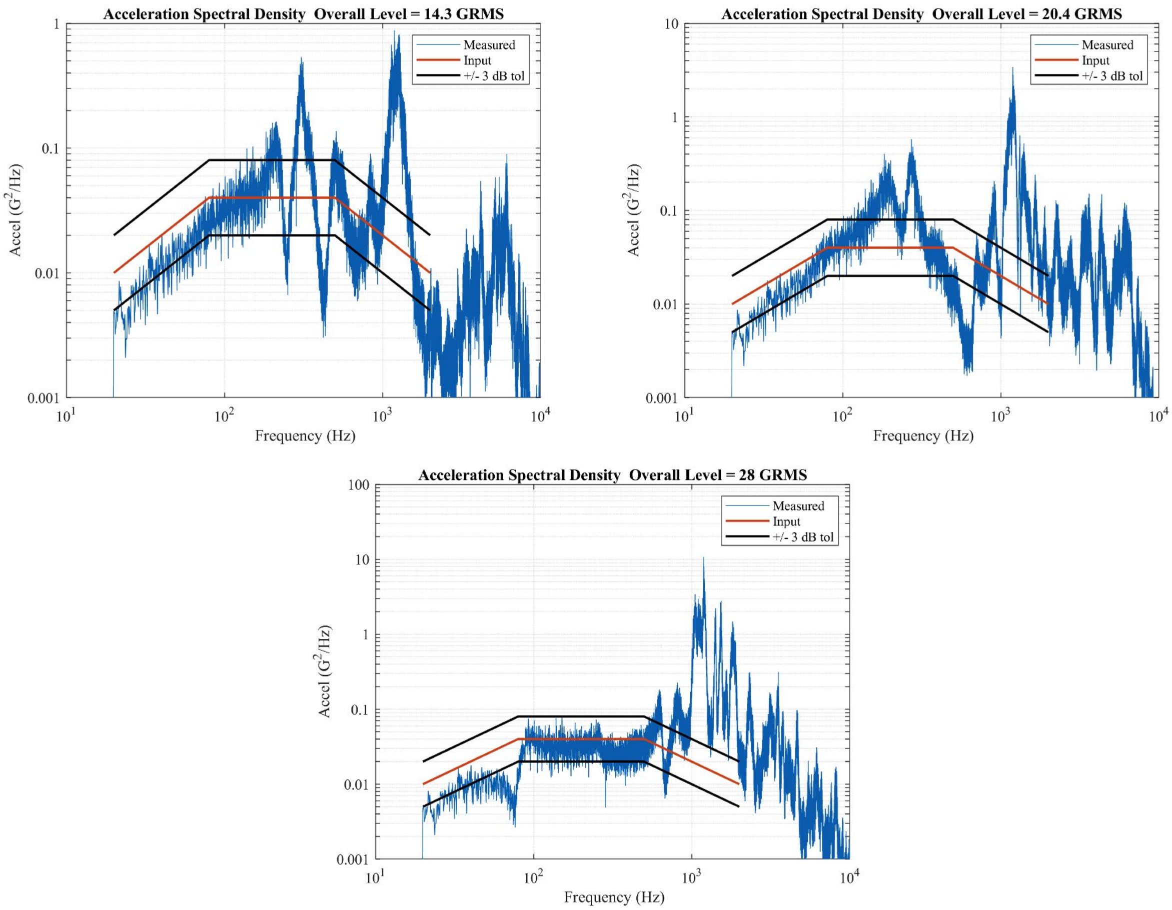


Fig. 17 Acceleration spectral density during random vibration test along x-axis (top left), y-axis (top right), and z-axis (bottom center)

panels to also test the longevity of the modular electronic connections. The test is conducted under normal room temperature and pressure conditions (FA 01).

Each on/off cycle takes about 30 seconds. Given our deadline, we have 12 days to continuously cycle HOMES. This means that if we assume that an average of six 30-second cycles will be conducted in the lunar habitat per day, we will be able to simulate 15 years in these 12 days. Furthermore, if we assume that three 30-second cycles will be conducted per day, then we will be able to simulate 30 years in these 12 days. After every three days, we conduct a dust verification test. We have constructed a simple rig so that each time we run a dust verification test, the rate of falling, quantity, and distribution of the lunar dust simulant remains relatively constant with each test. We have a camera attached to the rig so that we will be able to qualitatively record the rate at which dust is being pushed off of the panels after every three days. We will be showing side-by-side comparison videos of the first and last weeks' recordings to illustrate the longevity of the electronics in our final presentation. After each dust test, we continue cycling the electronics until the next dust test without exposure to lunar dust simulant. We will be repeating this procedure until the presentation submission deadline.

F. HOMES Demonstration

A demonstration of the functionality of HOMES must show effective and efficient lunar dust mitigation. Dust with qualitatively different levels of coarseness was sieved onto a fully constructed HOMES panel. The panel was allowed to run for 60 s. The dust propagated across the panel and was filmed with an Eakins Microscopic Camera. This experiment was repeated twice for two dust populations: a finer lunar dust with a maximum particle diameter of about $100\,\mu m$ and coarser lunar dust with a maximum particle diameter of $1200\,\mu m$.

The effectiveness of HOMES was assessed with image analysis tools in *Mathematica*. After 60 s of operation, the area of the dust coverage decreased by 98.92 % for finer dust particles and 99.89 % for coarser dust particles. For the required range of $0 - 50\,\mu$, the fine dust decreased coverage by 98.92 % and the coarse dust decreased coverage by 94.90 %. Thus, we can conservatively estimate that HOMES removes at least 98 % of dust in 60 s. Figure 18 shows the particle count decrease for each of the two cases. Appendix XIII.K shows the reference images before and after the use of HOMES for each trial. These preliminary results are promising as HOMES goes through further design modifications and show that HOMES is effective at clearing dust from its surface in a short period of time.

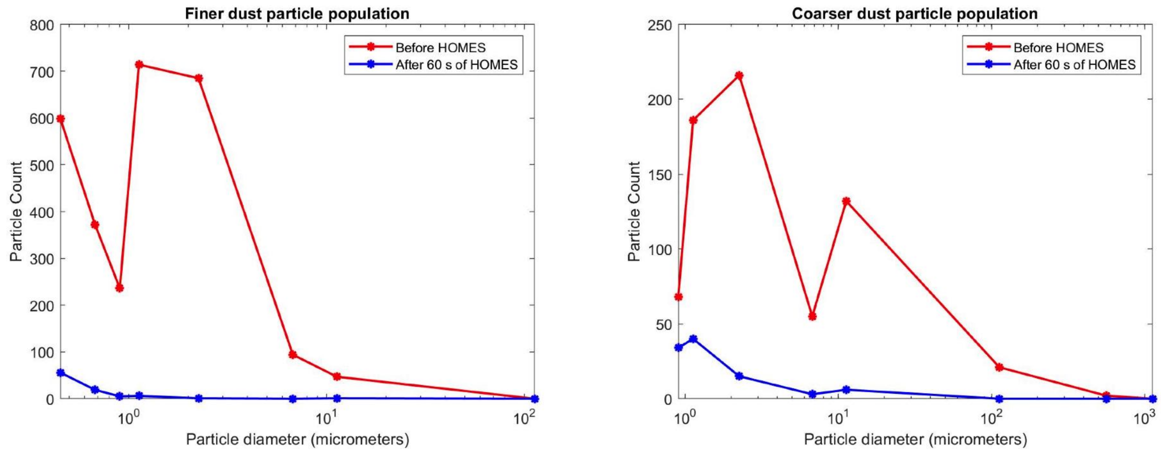


Fig. 18 Particle count for a given particle diameter for two dust populations

G. Current Progress and Next Steps

The LTE test currently remains in progress. At this point, we have conducted our first dust test and are continuously cycling HOMES. The LTE test will continue until the presentation submission deadline with a goal of demonstrating accelerated use corresponding to a simulated 15-30 year lifespan.

Due to limitations of the shaker table used for random vibration testing, HOMES was unable to be tested at qualification random vibration levels. Before flight, HOMES should be tested using these random vibration levels.

In addition to the tests performed, future testing could include thermal environment testing to expand the current use case to include use in the airlock of a lunar habitat or on the lunar surface. For these use cases, a thermal solution would need to be developed to maintain the high voltage electronics of HOMES at the proper temperature. Additionally, to validate these use cases, thermal simulations would need to be performed and testing would have to expand to include thermal and vacuum testing. This expanded testing program would include a liquid nitrogen dunk test to ensure survival of the physical panel and sensitive electronics when exposed to a large temperature shock. Additionally, a thermal vacuum test would be performed to ensure survival at low temperatures in a vacuum environment, simulating use on the lunar surface.

Other future testing could include additional mechanical testing to determine the point of failure due to fatigue, and tests where the panels are mounted in different orientations, such as vertically on the walls of the habitat, as well as testing more varied use cases. The mechanical testing could include fatigue testing and cryogenic fatigue testing, while tests of different use cases could include measuring connector effectiveness and the portion of dust removed when panels are mounted vertically instead of horizontally, or testing how dust is removed from objects left on top of the panels when turned on, simulating use as a work surface.

VII. Safety and COVID Protocols

The HOMES project has developed an extensive laboratory and COVID safety plan, that also has written approval by the Graduate Aerospace Laboratories at Caltech. A risk assessment and hazard control table can be found in Appendix XIII.B. The hazard control table summarizes the trainings, personal protective equipment (PPE), and safety tools required to work in the lab. Examples of PPE include respiratory masks for handling lunar dust simulant, high-voltage resistant gloves, and safety goggles. The lab was consistently stocked with appropriate PPE and safety equipment. To keep track of inventory, an e-log book was used for lab members to record when they left the lab, what supplies they used, and to monitor if lab clean-up procedures were followed. HOMES also had a buddy system. All high-voltage and high-risk laboratory activities required at least one other person present who have both undergone relevant training. There was also a virtual video stream of the lab that allowed for other lab members to monitor teammates doing high risk activities. Furthermore, any high-risk activities required a detailed procedure write-up that was in compliance with safety measures and assessed to minimize risk. All participants in the lab also complied with Pasadena and Caltech's COVID protocols. Lab capacity was monitored, masks were required, and all in-person team members participated in Caltech's COVID surveillance testing, where testing is required two times per week. There were no COVID cases reported for any of the HOMES team members.

VIII. Path to Flight

A. Immediate Requirements

In order to prepare HOMES for implementation on the Moon, there are a few critical modifications that must be made. HOMES was initially designed with an alumina plate covering the EDS PCB, giving astronauts a solid surface to work/walk on while protecting the EDS technology. However, through testing we have found that the alumina panel is too thick for EDS to work effectively through it. Another way of protecting the EDS PCB which would support the effectiveness of EDS would be to use an abrasion resistant spray coating with a high dielectric strength, such as alumina ceramic through magnetron sputtering. Unfortunately we did not have access to such materials but if HOMES were to be implemented in space this coating would be crucial.

Reducing the power draw is another important task in order to increase the viability of HOMES as a scalable EDS implementation for habitat dust mitigation. We could notably design a modification of the power supply circuit to be a half bridge circuit, which would allow for potentially lower power draw and faster rise times.

Another critical modification would be to replace the Arduino in the current electronics box with its own dedicated circuit or smaller microprocessor. This change would decrease the size of the electronics box drastically.

In regards to testing, the random vibration test was only conducted at the minimum workmanship level due to limitations of the shaker table used for testing. Before flight, HOMES would need to be tested at qualification random vibration levels. Depending on the results of the qualification test, it may be necessary to design packaging that protects HOMES against the maximum expected flight levels of random vibration. In addition, lifetime tests are a work in progress and will need to continue for a few more months to finish verification of the longevity of the technology.

B. Continuing Concept Development

One way to expand upon the current use cases for HOMES would be to further explore thermal management on the panel body to allow for use in a larger temperature range. The current design only allows for use within habitats on the lunar surface, in constant temperature and pressure environments. But we could design a thermal solution so that HOMES could be used in an airlock, where it briefly reaches significantly lower temperatures and pressures. The next step would be to develop a thermal solution such that HOMES could be used completely outside of habitats, where it would permanently experience the lowest temperatures on the surface of the moon at nearly vacuum.

We could also explore the limitations of HOMES through further mechanical fatigue testing. In our past testing of HOMES, we have impact and load tested once per panel, but these loads could be applied hundreds of times to study fatigue over time. Tests like these could validate HOMES for more intensive applications such as on a workbench, where loads are applied frequently.

Finally, future iterations of HOMES could involve developing smaller, lower mass panels, panels of different shapes, panels with joints that can be attached at various angles, and flexible panels.

IX. Conclusion

HOMES has demonstrated a successful modular electrodynamic dust shielding system, offering the next step in habitat lunar dust mitigation aiding the establishment of a human presence on the Moon. Multi-panel demonstrations have shown effectively movement of 98.9% of applied dust within 60 seconds to a desired collection location. Impact and load testing have also proven HOMES's ability to withstand loads of 442.8 N and impact from 100 kg falling 24.7 cm, beyond expected from an astronaut in lunar environments. Random vibration testing showed that HOMES can withstand NASA's minimum workmanship random vibration test levels for electrical, electronic, and electromechanical hardware that weighs less than 50 kg. Long-term effectiveness testing, which is ongoing, will further show the capabilities of HOMES for extended use. With the successful completion of all of these tests, HOMES will be qualified to TRL 5.

With the continuation of the testing program, HOMES could be qualified for use in human lunar mission by Artemis III. With further development, the modular technology could also be extended to airlock and lunar surface environments and non-lunar environments. Promising results of scalability and modularity show that the design can effectively mitigate dust in a variety of habitats and surfaces, enabling extended human habitation and activity on the moon for the NASA Artemis missions and beyond. Through the testing performed, we have demonstrated that HOMES has met all the Functional Requirements outlined in this project, and has the capability to significantly reduce the risk of lunar dust on astronaut health and mission success in future space missions.

X. Project Timeline

Item	Dates	TRL Pending	Description
First Team Meeting	9/16/20	N/A	First Caltech BIG Idea Team meeting before the NOI with 15 members.
Notice of Intent Submission	9/25/20	N/A	Submission of HALOS NOI for astronaut visor protection.
Rev 0 Design	9/26/20 - 12/1/21	2	Initial concept design phase for HOMES.
Concept Design Review	10/18/20	2	Internally reviewed two competing designs and selected the final concept for BIG Idea Challenge.
Preliminary Design Review	11/18/20	2	First design review for early HOMES concept with Caltech and JPL faculty.
Submission of Proposal	12/13/20	2	Submission of HOMES proposal
Team Notified of Selection	1/29/21	2	HOMES project awarded ~$180k by BIG Idea Challenge.
Rev 1 Design Phase	1/4/21 - 3/25/21	2	Design refinement of HOMES based on system architecture described in the proposal with judge's feedback implemented.
Rev 1 Review	3/26/21	2	Formal design and testing review with rev 2 HOMES with Caltech and JPL faculty.
Rev 1 Manufacturing	4/16/21 - 7/21/21	2	Manufacturing and assembly of rev 1 HOMES prototypes for low fidelity testing.
First Successful EDS Test	5/21/21	3	First successful EDS test with lunar dust simulant using benchtop EDS power supply.
Mid-Point Report	5/20/21	3	Deadline of Mid-Point Report for BIG Idea judges.
Notified of Pass Status	6/10/21	3	Team notified of pass status and second installment of funding.
Rev 1 Testing	7/22/21 - 8/1/21	4	Impact, quasi-static load, and electrical testing of rev 1 prototype.
Rev 2 Design	7/19/21 - 8/18/21	4	Rev 2 redesign increasing panel size and changing material.
Rev 2 Manufacturing	8/3/2021 - 10/17/21	4	Manufacturing and assembly of rev 2 final HOMES prototypes.
Rev 2 High Fidelity Testing	10/18/21 - 10/24/21	5	High fidelity impact, quasi-static load, vibration and full system functionality testing of final rev 2 prototypes.
Rev 2 Lifetime Testing	10/22/21 - 12/22/21	5	15 year equivalent accelerated electronic lifetime testing of two panels connected while measuring dust removal effectiveness.
Technical Paper & Verification Demonstration	10/27/21	5	Submission deadline for technical paper and verification demonstration.
System Acceptance Review	11/4/21	5	Final system acceptance review of HOMES with Caltech and JPL faculty.
Presentation and Poster Submission	11/11/21	5	Submission deadline for presentation and poster.
BIG Idea Forum	11/17/21-11/18/21	5	Culmination of NASA 2021 BIG Idea Challenge
SciTech Conference	1/3/22 - 1/7/22	5	Finalists for undergraduate team research paper and presentation of HOMES.

XI. Final Budget

A. Description of Expenditures

HOMES's budgetary plans have remained largely the same as what was initially outlined in the team's proposal in December, and updated in May. There have however been some changes, the major one being the removal of travel and registration costs associated with the team's original participation in the Big Idea/ASCEND conference in Las Vegas, since moved to an online format.

As planned, Caltech has partially subsidized the labor costs of 8 students for the 2021 Summer Undergraduate Research Fellowship (SURF). To speed up the development of HOMES over the rest of the summer, compensation and benefits were also provided to team members working full time on the project between the dates of August 23rd and September 24th, including taking on a Visiting Undergraduate Research Program (VURP) Fellow. See Appendix Section XIII.E.1.

Indirect costs are the same as those estimated in the mid-project report, and are recapped in Appendix Section XIII.E.2.

Material costs have continued at a pace similar to that outlined in the initial report. We have broken these down into general categories in Appendix Section XIII.E.3, and by phase in Figure 19 (see below). The Miscellaneous category includes the purchase of safety equipment, a high performance desktop computer, generic office and laboratory supplies, and other such expenses.

Additionally, costs associated with the use of the Caltech student machine shop for manufacturing purposes were $1,000, while those associated with the use of the GALCIT (graduate aerospace) machine shop to machine ceramics amounted to $5,740. $550 was also invested into testing the 3D printing of PEEK.

Travel costs, originally accounted for in the budget outlined in our proposal and mid-project report, have been removed since the cancellation of registration fees and the in-person conference in Las Vegas. These funds were either redirected to material costs and additional labor costs, or remain unused.

Category	First Phase	Second Phase
Travel	$0.00	$0.00
Materials	$26,289.87	$23,030.29
Labor	$26,480.00	$19,991.42
Manufacturing	$3,370.00	$3,920.00
Total IDCs	$16,715.88	$28,883.86
Award total	**$83,579.41**	**$96,419.28**
Amount spent	**$72,855.75**	**$75,825.57**
Amount remaining	**$10,723.66**	**$20,593.71**

Fig. 19 Breakdown of expenditures by phase of funding

B. External Sponsorships and Grants

We were lent several COMSOL Multiphysics licenses free of use by our mentor Richard Abbott of LIGO, as well as a HI-POT tester for arcing tests of our initial EDS panels. We also completed a design review of our high voltage switching circuitry with several engineers from Second Order Effects, an electrical engineering consulting firm based out of El Segundo, CA. Aside from this expertise, software and testing equipment, the HOMES team has received no direct financial sponsorships or partnerships from any actors external to the Challenge.

XII. Acknowledgments

The HOMES team would first of all like to thank NASA, NIA, and the NASA BIG Idea Challenge 2021 Jury for the opportunity to further design, build and test prototypes of an experimental technology as undergraduate students. Thank you to the Space Grant Consortium for their help in acquiring Phase 2 funding.

We are also especially grateful to those who have provided the team with expertise and equipment. Special thanks to our advisors Dr. Soon-Jo Chung, Dr. Michael Mello and Dr. Charles Elachi of Caltech, Richard Abbott of LIGO, and Dr. Jason Kastner and Dr. Manan Arya of JPL for their continued support and advice throughout the project.

We'd also like to thank Martha Salcedo, Tasha Hsu, Lin Ling, Marionne Epalle, Jamie Meighen-Sei and all of the other Caltech administrators who facilitated the team's success.

Thank you as well to Second Order Effects for their expertise in high voltage circuit and PCB design, and the opportunity to hold a design review.

XIII. Appendix

A. Concept of Operations

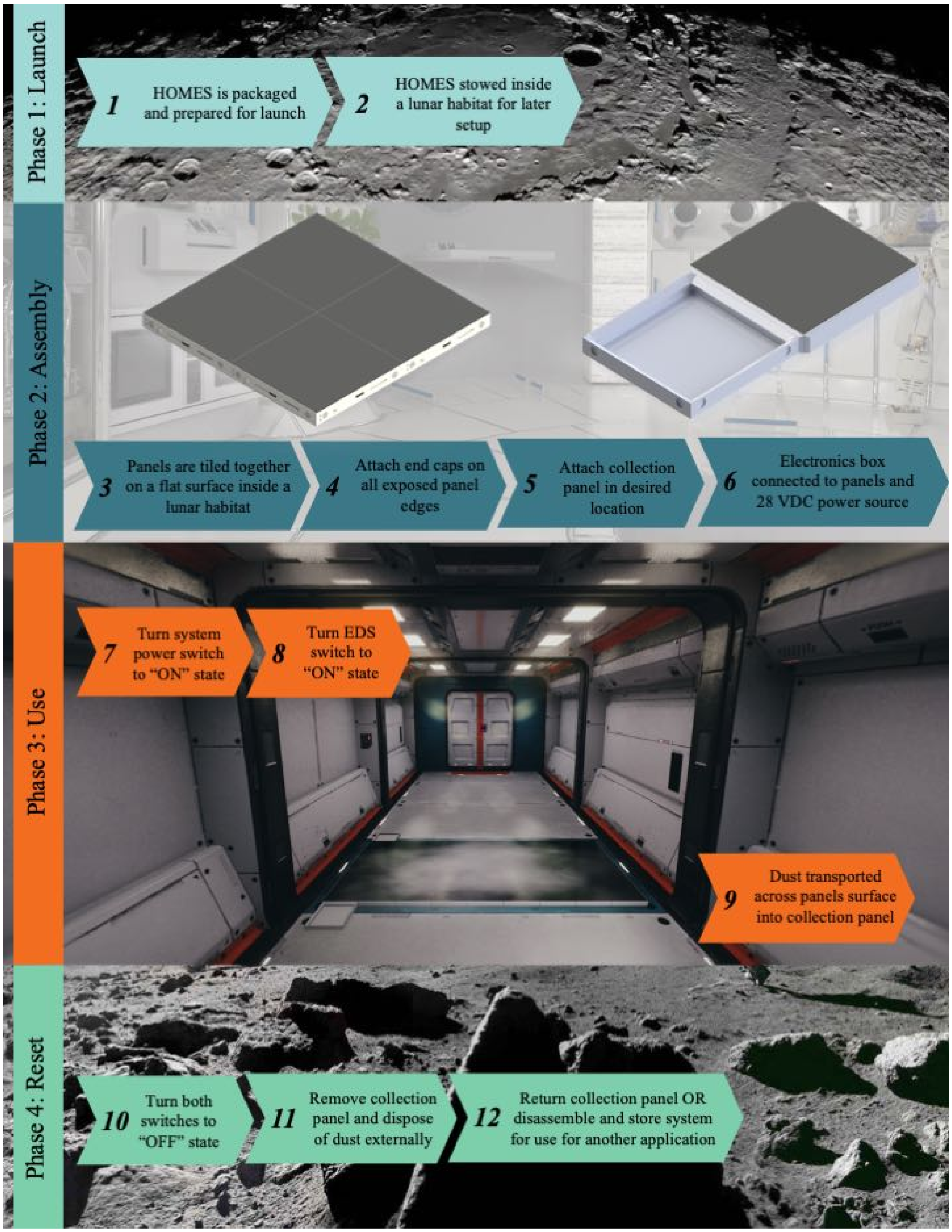


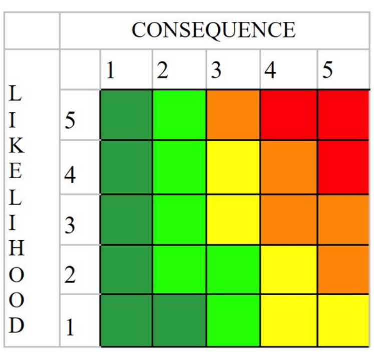
Fig. 20 Concept of operations

B. Safety Tables

Table 21 enumerates residual risks after enacting appropriate mitigation strategies. See Fig. 22 for the risk rating key.

H# - Hazard	**Control and Residual Risk Rating**	
H1 - High voltage electrocution	High voltage safety training, PPE and tools are required before use. Maintaining distance and proper delineation of boundaries and failsafes avoids interaction with live high voltage equipment.	5, 1
H2 - Electronics starting fire	Safe power connections and selection of properly rated connectors reduces likelihood of fires. Proper training and knowledge of fire extinguisher use and evacuation procedures reduce risk of injury.	4, 1
H3 - Personnel Safety	Safety training and PPE (respirators, gloves, thermal/electrical insulation) is required before all hazardous work. An oxygen monitor is placed on nitrogen sources.	2, 1
H4 - Simulant poisoning	Gloves, safety glasses, and NIOSH approved respirator will be worn when handling simulants.	4, 2
H5 - Pressurized N2 explosion	Proper procedure will be followed for storage and handling of nitrogen gas cylinders.	5, 1
H6 - Tool injury	Safety training for powered tools will be required before use. PPE (safety glasses, gloves, etc.) and engineering controls (guards, E-stops, etc.) are required.	3, 1

Fig. 21 Safety Risk Table



Likelihood key: 1- Very unlikely, 2- Unlikely, 3- Possible, 4- Likely, 5-Expected

Consequence key: 1- Negligible impact, 2- Minor impact, 3- Moderate impact, 4- Significant impact, 5- Significant irreversible impact

Color key (priority): Dark green- Very low priority/No concern, Green- Low priority/Mild concern, Yellow- Medium priority/Moderate concern, Orange- High priority/Significant concern, Red- Very high priority/Immediate concern

Fig. 22 Risk Rating Key

C. Load Testing

During the design of HOMES, the panels were continually tested in finite element simulations. In order to ensure the material parameters were correct, to obtain a Poisson's ratio, and to match the finite element model closer to reality, materials used for the panel walls (PEEK) and the top EDS PCB (FR-4) were subject to tensile testing. Dogbone specimens of each material were cut following ASTM D638 standards (with dimension adjustments to fit inside available stock). Results were characterized using strain gage and DIC metrologies.

The key to the DIC metrology is to deposit fine, random speckle pattern onto the surface of the test specimen. The pattern is deposited through a spraying procedure using commercially available, flat white and flat black spray paint. The test specimens used were: (1) an FR-4 dogbone specimen of the top EDS PCB with traces aligned horizontally (transverse) of around 1.51 mm thickness and 9.95 mm width; (2) an FR-4 dogbone specimen of the top EDS PCB with traces aligned vertically (longitudinally) of around 1.51 mm thickness and 9.92 mm width, shown in Fig. 23; (3) a PEEK Dogbone specimen of the panel wall material with thickness of 6.83 mm and Width of 11.17 mm; (4) a PEEK Dogbone specimen of the panel wall material with thickness of 6.82 mm and Width of 11.18 mm.

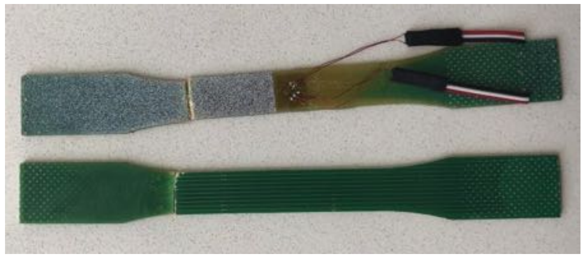


Fig. 23 FR-4 Test Specimen with Vertical (Longitudinal) Traces, DIC Speckle Pattern, and Strain Gage

The tensile test was conducted with a 25kN ADMET axial-torsional load frame shown in Fig. 24. This uses a 4 megapixel CCD camera with a 35mm imaging lens to acquire high-resolution monochrome images of the speckled surface of our test specimen. The specimen is illuminated using an LED light source. A diagram of the testing set-up is included in Fig. 24.

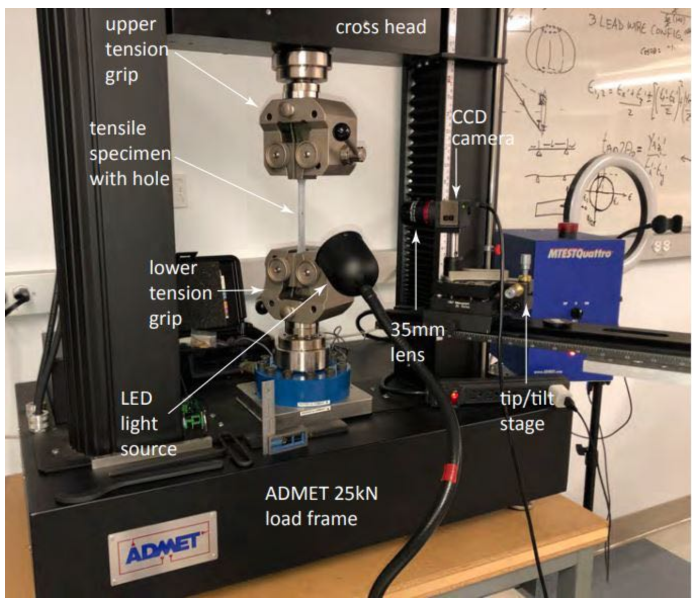


Fig. 24 Axial loading setup using a 25kN ADMET axial-torsional load frame with USB camera and LED light source for 2D Digital Image Correlation (DIC) [16]

1. FR-4 Tensile Testing

We denote specimen (1) of the FR-4 with horizontal traces as FR4 (H), and specimen (2) of the FR-4 with vertical traces as FR4 (V). Loading conditions of FR4 (H) and FFR4 (V) are detailed in Fig. 25.

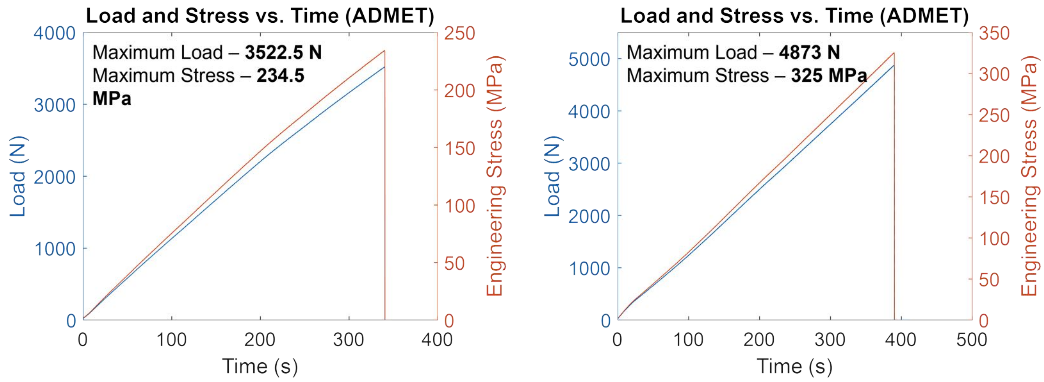


Fig. 25 Loading Conditions for FR4 Tensile Testing. FR4 (H) on the LEFT, and FR4 (V) on the Right.

Stress vs. Strain Curves, shown in Fig. 26, were obtained using both DIC and Strain Gage data. This allowed for two separate determinations of Young's Modulus by examining the linear portion of the stress vs. strain curves. Similarly, examining the linear portion of the transverse vs. longitudinal strain plots, shown in Fig. 27, allowed the determination of the Poisson Ratio.

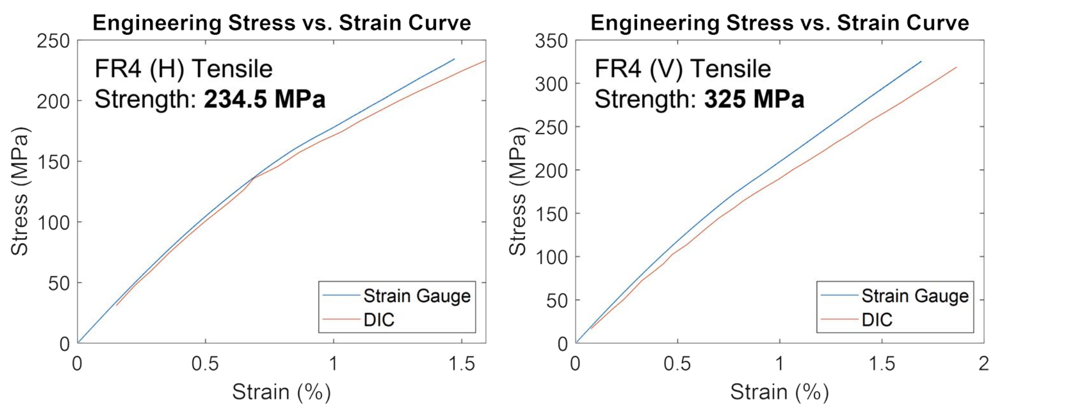


Fig. 26 Stress vs. Strain Curves from FR4 tensile testing. FR4 (H) on the LEFT, and FR4 (V) on the Right.

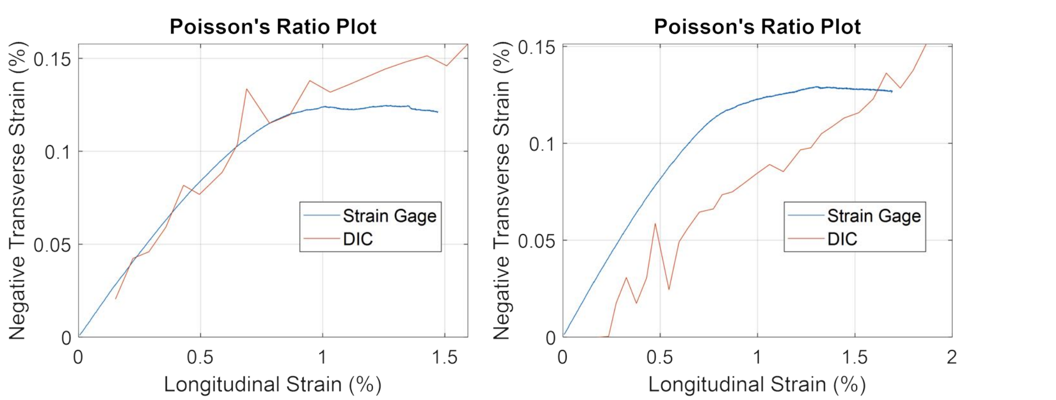


Fig. 27 Poisson Ratio Plots from FR4 tensile testing. FR4 (H) on the LEFT, and FR4 (V) on the Right.

Table 8 contains a summary of the tensile testing results and the FR4 material parameters.

Specimen		Crosshead Speed (in/min)	Poisson's Ratio	Young's Modulus (GPa)	Failure Strain (%)	Tensile Strength (MPa)
FR4 (H)	Strain Gage	0.02	0.169	21.0	1.47	235
	DIC		0.169	20.4	1.59	
FR4 (V)	Strain Gage	0.02	0.168	24.0	1.69	325
	DIC		0.110	22.9	1.87	

Table 8 FR-4 with EDS Traces - Tensile Testing Summary

2. PEEK Tensile Testing

Two tensile tests were conducted for the PEEK material.

For PEEK (3), only DIC was used to characterize the tensile testing during the elastic portion. Looking at the stress vs. strain and tranvserse vs. longitudinal strain plot, Young's Modulus and the Poisson ratio were able to be determined from the slope. Both linear fits are included in Fig. 28.

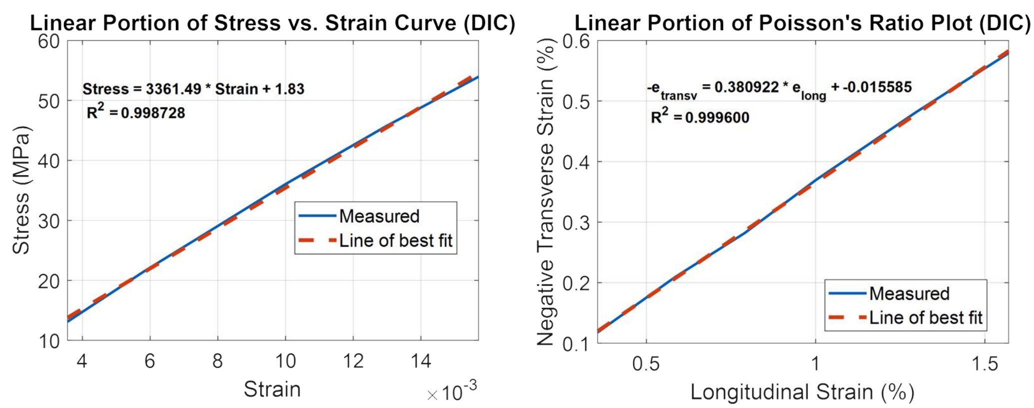


Fig. 28 Linear Fit for Stress vs. Strain and Tranverse vs. Longitudinal Strain for PEEK (3) Tensile Testing.

For PEEK (4), both strain gage and DIC were used. The use of DIC for PEEK (4) allowed the determination of the failure strain, since the Strain Gage would debond at the high strains experienced before failure.

The Stress vs. Strain Curve, shown in Fig. 29, was obtained using both DIC and Strain Gage data. This allowed for two separate determinations of Young's Modulus by examining the linear portion of the stress vs. strain curves. Similarly, examining the linear portion of the transverse vs. longitudinal strain plots, shown in Fig. 29, allowed the determination of the Poisson Ratio.

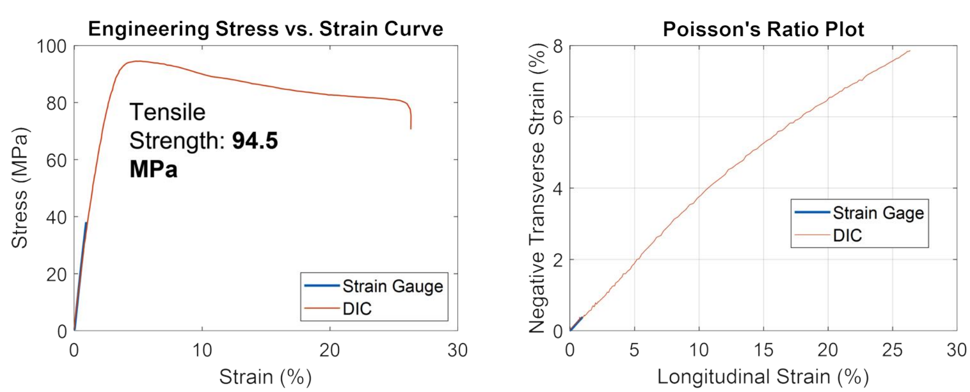


Fig. 29 Stress vs. Strain and Tranverse vs. Longitudinal Strain for PEEK (4) Tensile Testing.

Table 9 contains a summary of the tensile testing results and the PEEK material parameters.

Specimen		Poisson's Ratio	Young's Modulus (GPa)	Failure Strain (%)	Tensile Strength (MPa)
PEEK (3)	DIC	0.381	3.36	N/A	N/A
PEEK (4)	Strain Gage	0.404	4.2	N/A	94.5
	DIC	0.405	3.5	26.3	

Table 9   PEEK - Tensile Testing Summary

D. Finding Optimal Rise and Fall Times of Frequency

The team was originally under the assumption that a slow rise and fast descent in frequency would move dust particles with greater force. To test whether altering the rise and fall times of the frequency would affect the force across the EDS panel, models with constant rise time with varying fall times were simulated in COMSOL. As in the previous voltage and frequency optimizations, each model was compared and evaluated by the calculated force across the panel. As seen in Fig. 30, It was found that varying fall times of frequency had no effect on the force across the panel. Thus, the team concluded that altering fall times for a fast rise and sharp descent would not be necessary.

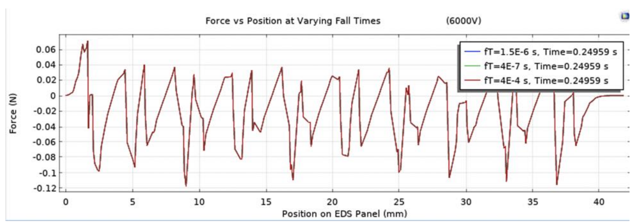


Fig. 30   Force across surface of EDS panel at various fall times of frequency. NOTE: graphs of varying fall times are stacked on top of each other.

E. Budget Breakdown

1. Labor Costs

Expense name	# of students involved	total	Phase
SURF stipends	8	$26,480.00	1
VURP fellowship	6	$3,312.00	2
September wages	6	$13,133.40	2
Benefits	1	$3,546.02	2
Total		**$46,471.42**	

2. Indirect Costs

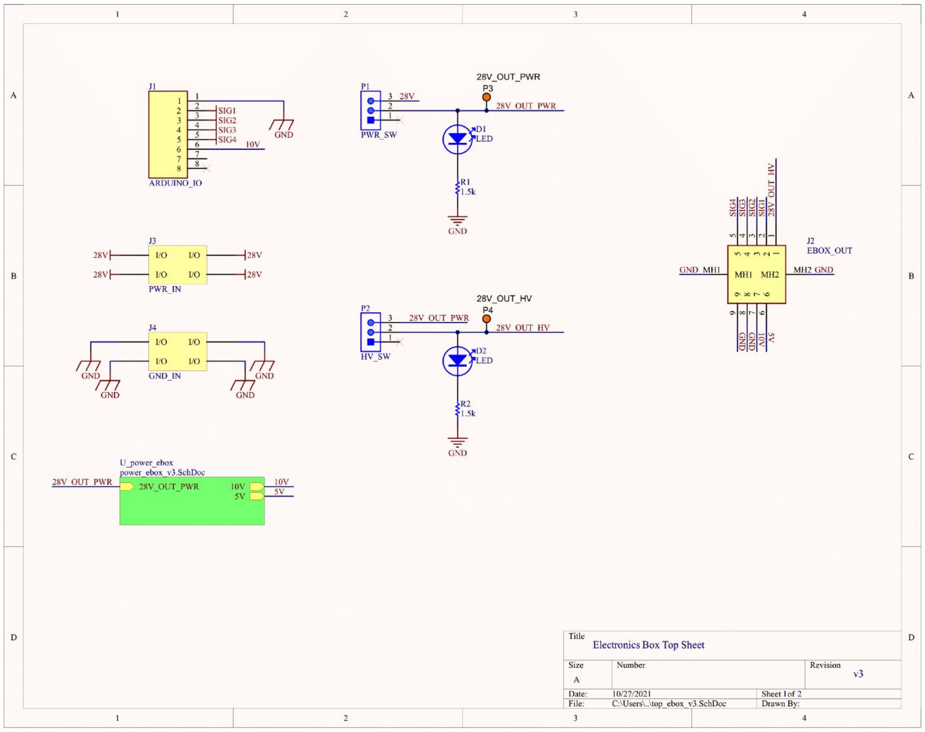
Expense name	Total	Phase
Caltech IDC	$16,715.88	1
Caltech IDC	$16,883.86	2
UCSD IDC (Space Grant Consortium)	$12,000.00	2
Total	**$45,599.74**	

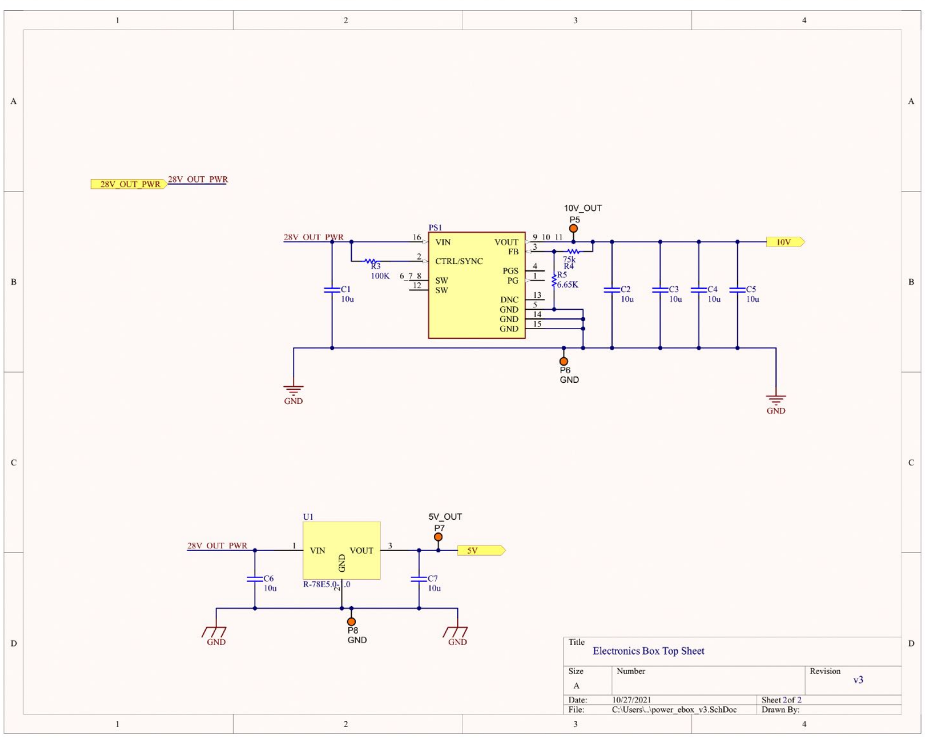
3. Material Costs

Expense category	Total	% of total
Electronics & components	$18,380.98	37.27%
PCBs	$4,431.04	8.98%
Testing equipment & materials	$7,002.20	14.20%
Panel manufacturing & materials	$10,075.32	20.43%
Miscellaneous	$9,430.62	19.12%
Total	**$49,320.16**	**100.00%**

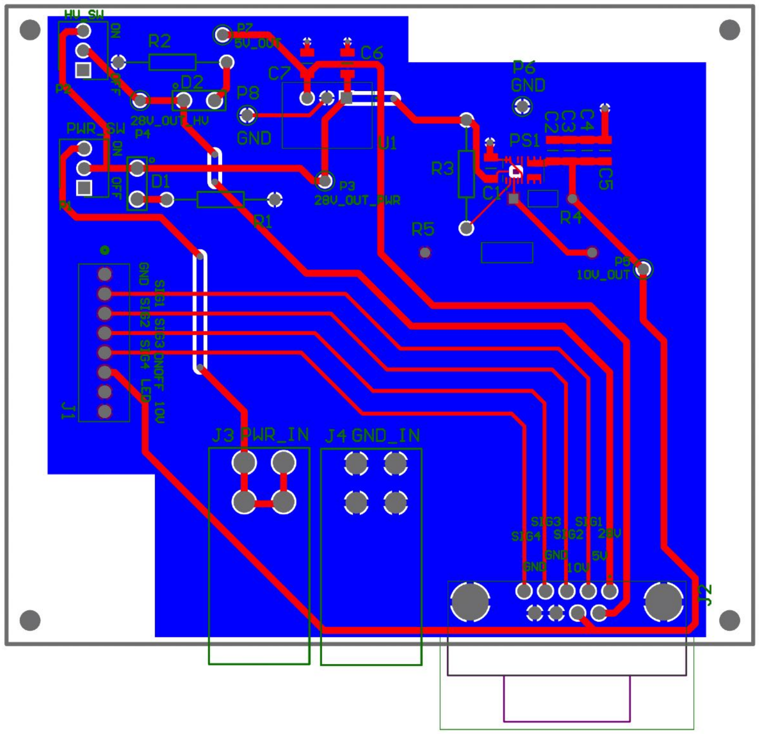
F. Electronics Box Circuit and PCB Design

1. Electronics Box Circuit Schematics (ALTIUM DESIGNER)

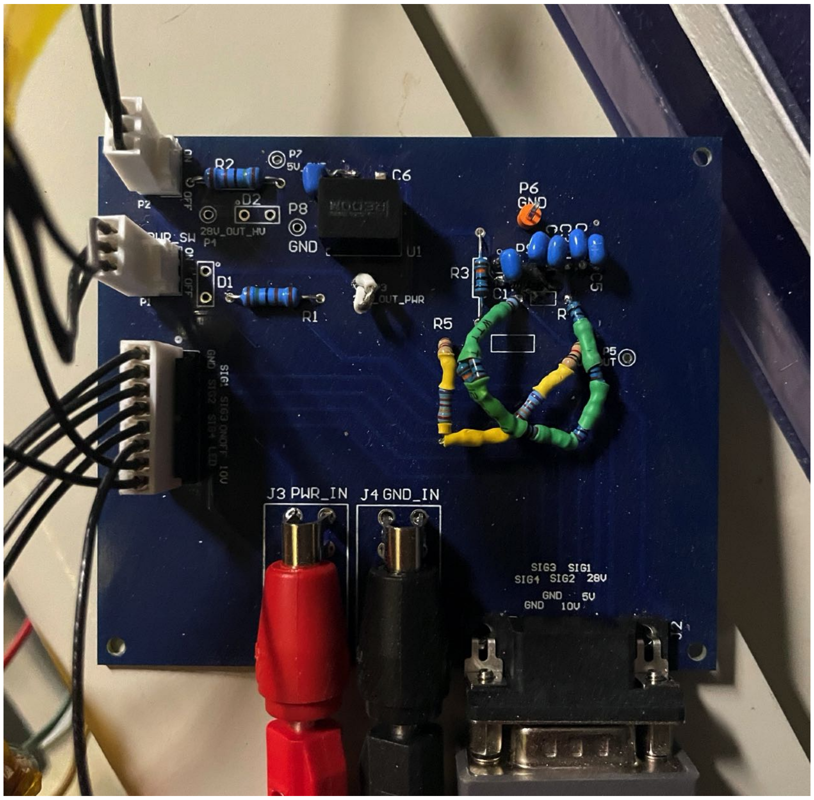




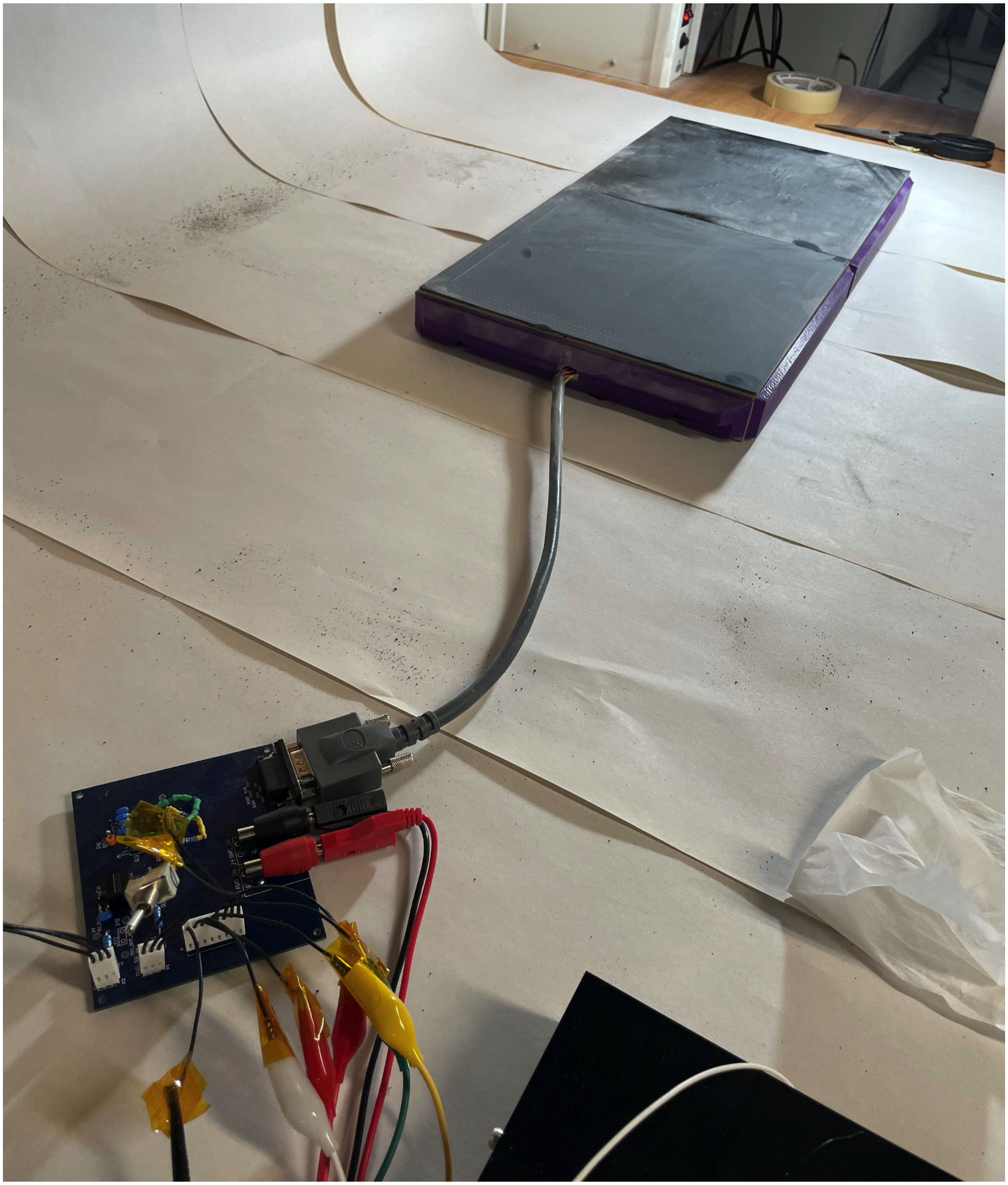
2. Electronics Box PCB CAD. Ground Plane in Blue



3. Electronics Box PCB Pictured During LTE Test (Casing Removed)

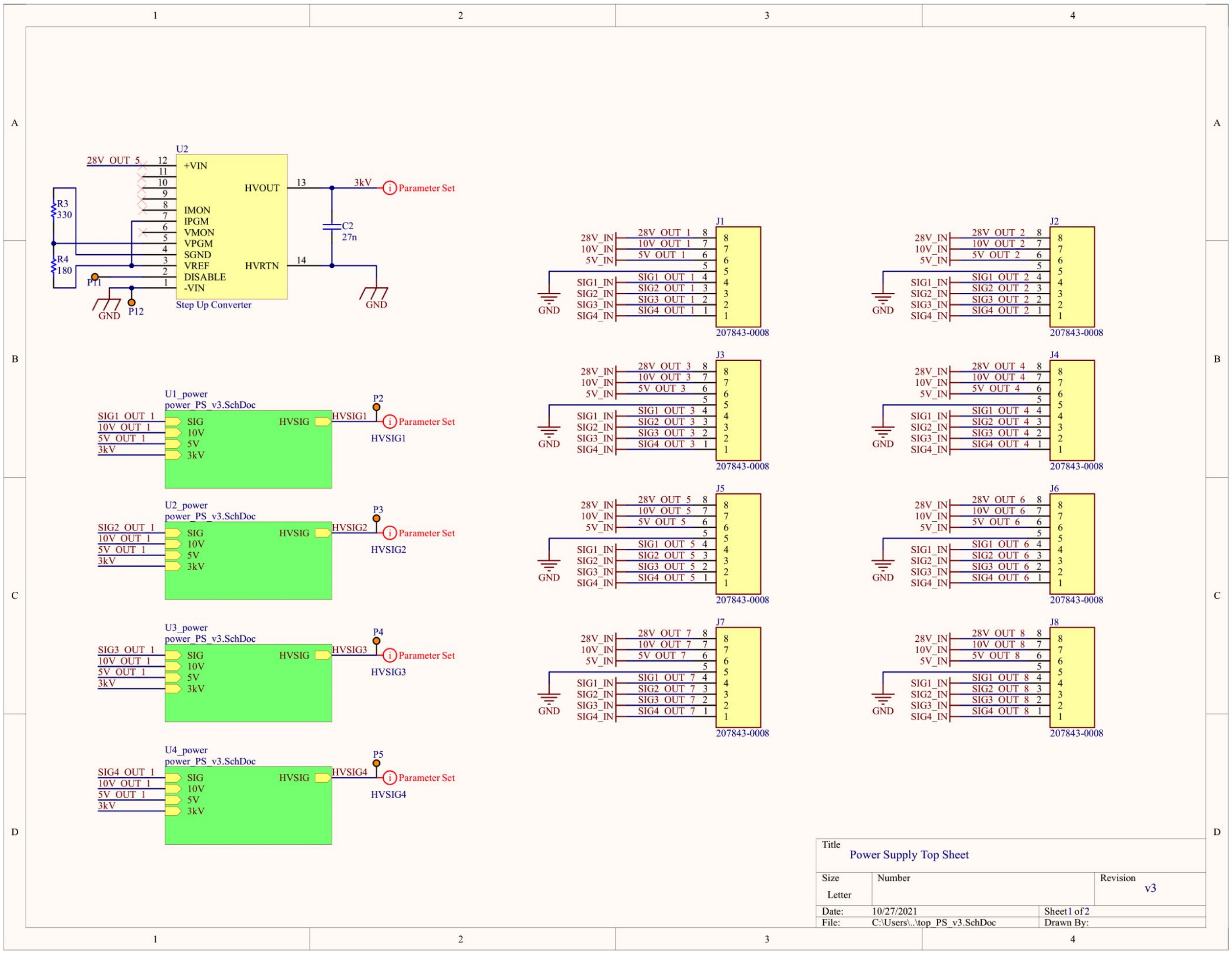


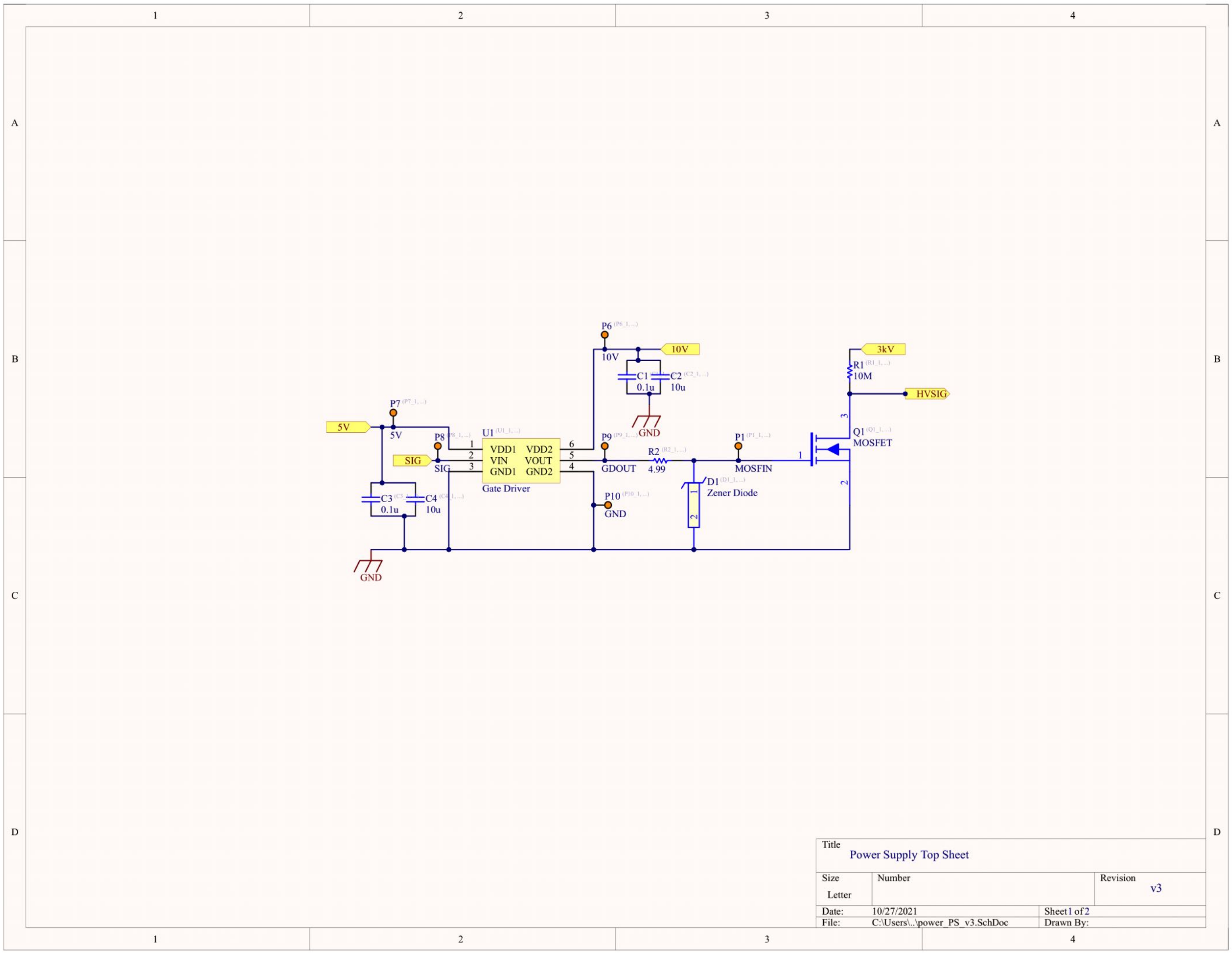
4. Electronics Box Functionality Test Set Up



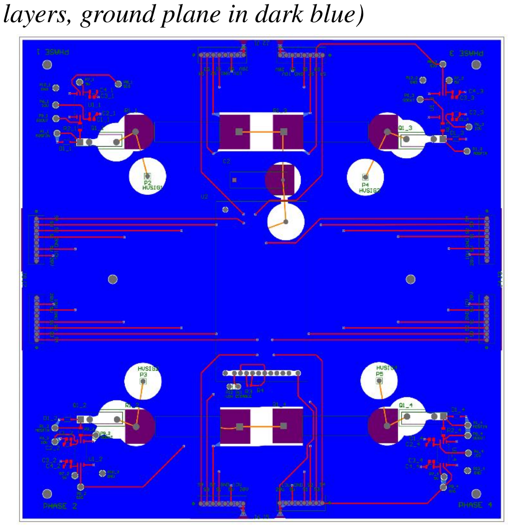
G. Power Supply (in-board) Circuit and PCB Design

1. Power Supply Circuit Schematic

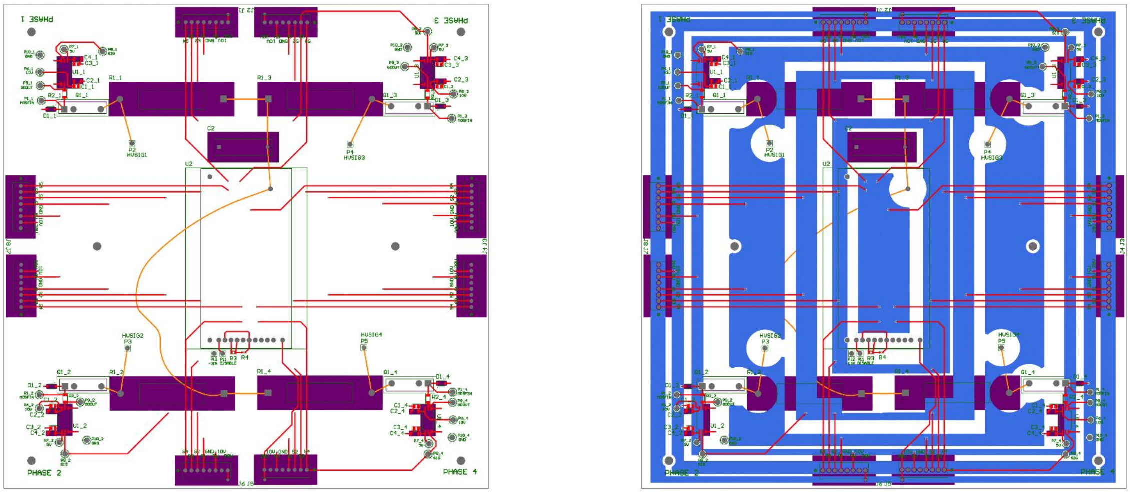




2. *Power Supply PCB Layout (All layers, ground plane in dark blue)*



3. Power Supply PCB Layout (No pours on left, with power distribution loops on the right)



H. EDS PCB Progressive Designs

1. EDS PCB First Version: Rigid 96 Electrode Test Panel, 2 layers

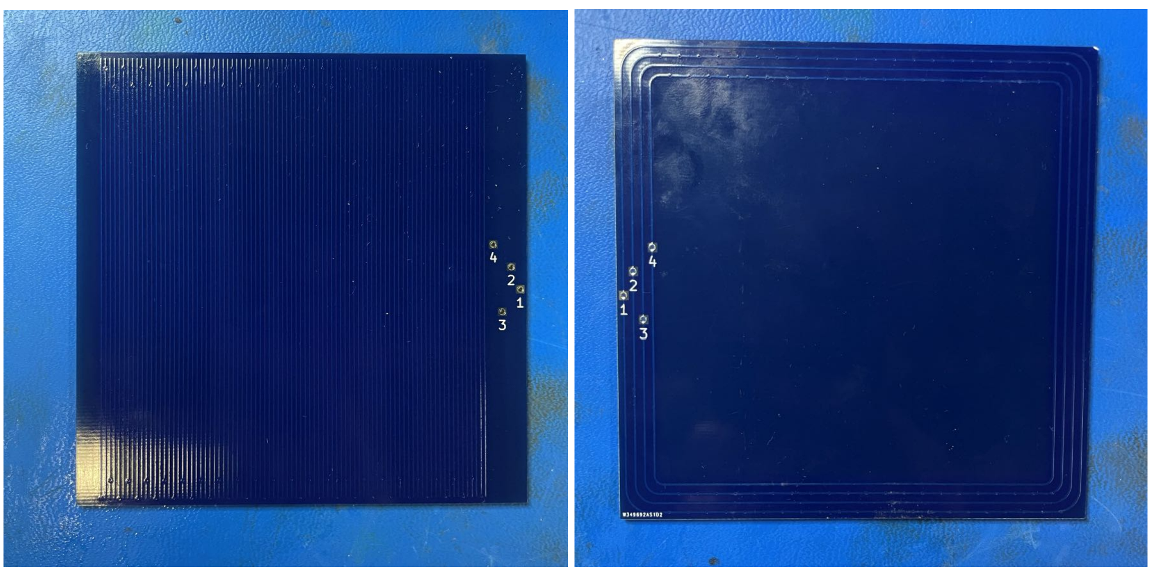


Fig. 31 First EDS PCB (top side on the left, bottom on the right), designed on two layers as a proof of concept for EDS prior to the development of modularity and scalability. Improvements were made on the routing in subsequent designs to allow for the electrodes to span the entire panel

2. EDS PCB Second Version: larger panel, 4 layers for better routing

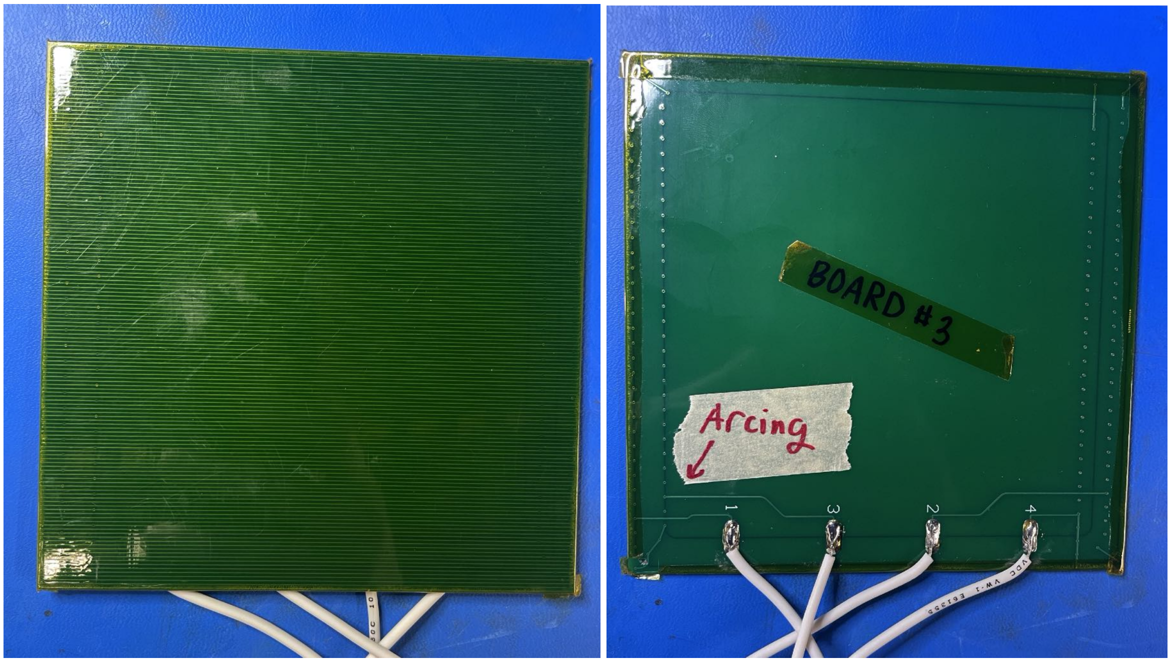


Fig. 32 Second EDS PCB (top side on the left, bottom on the right), designed on four layers for superior routing, allowing for 144 electrodes to span the entirety of the board's top surface.

3. Flex PCB EDS PCB Prototype

Fig. 33 Prototype of flexible PCB implementation of EDS board for durability. Despite the substrate being polyimide film, arcing was observed, and manufacturer delays and defects caused HOMES to remain with the rigid FR4-type PCB for later prototypes

4. Final EDS PCB Design

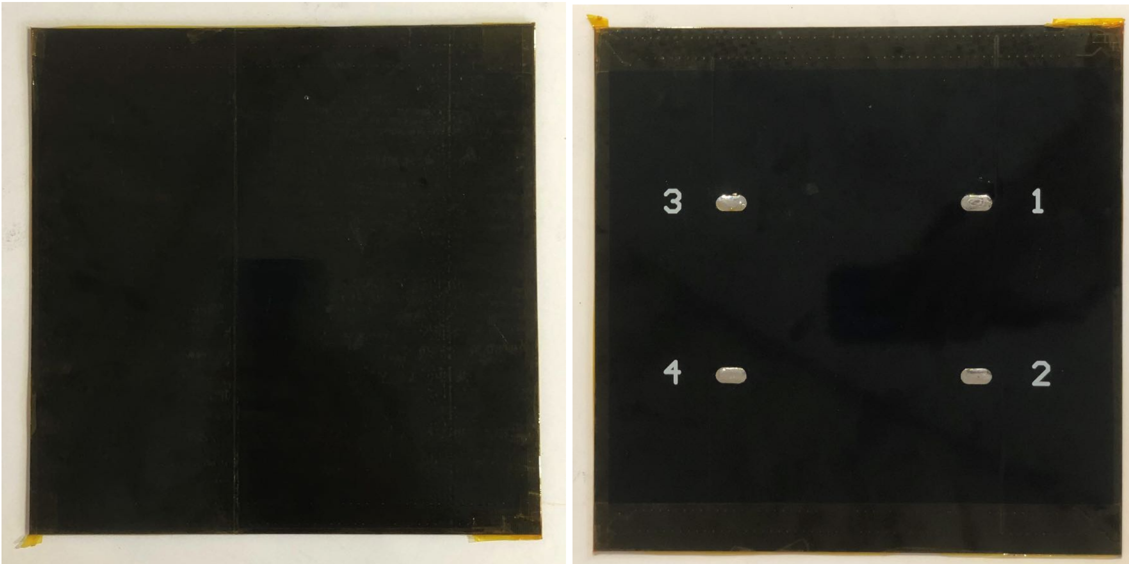


Fig. 34 Final EDS PCB implementation. 256 electrodes are split into 4 phases, the routing allows for the entire panel to be spanned by EDS, and solder pads are centered for soldering wires to the Power Supply PCB during full panel assembly

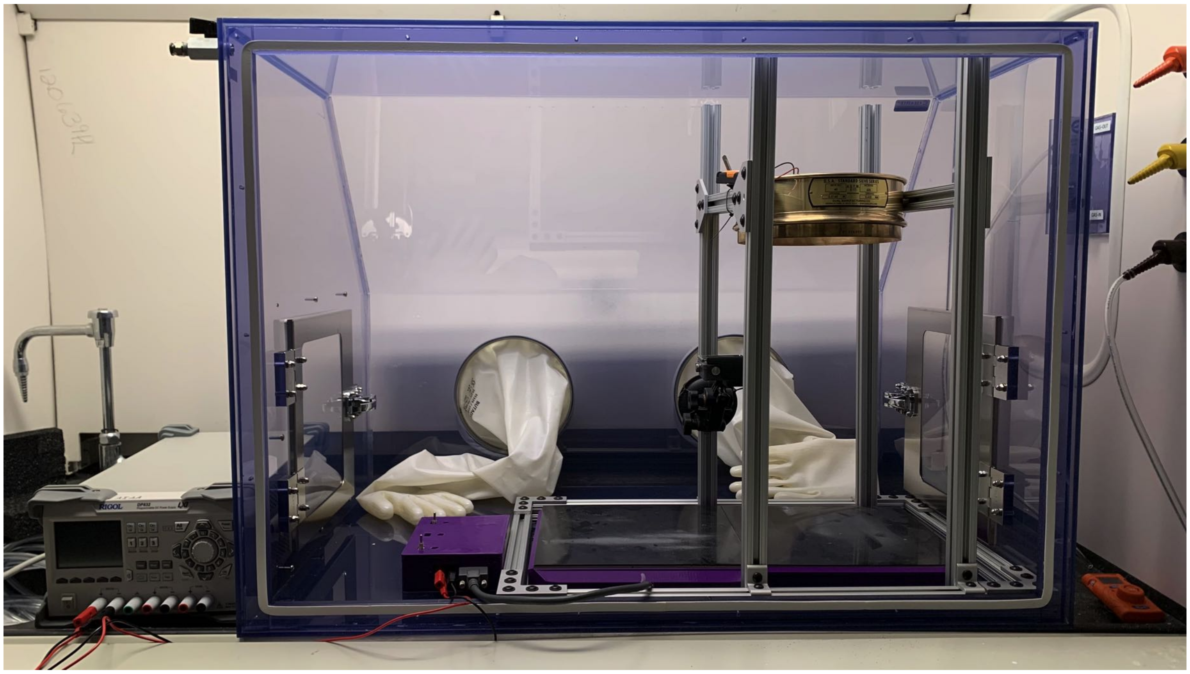
I. Mechanical Modularity Demonstration

1. Before Panel Connection

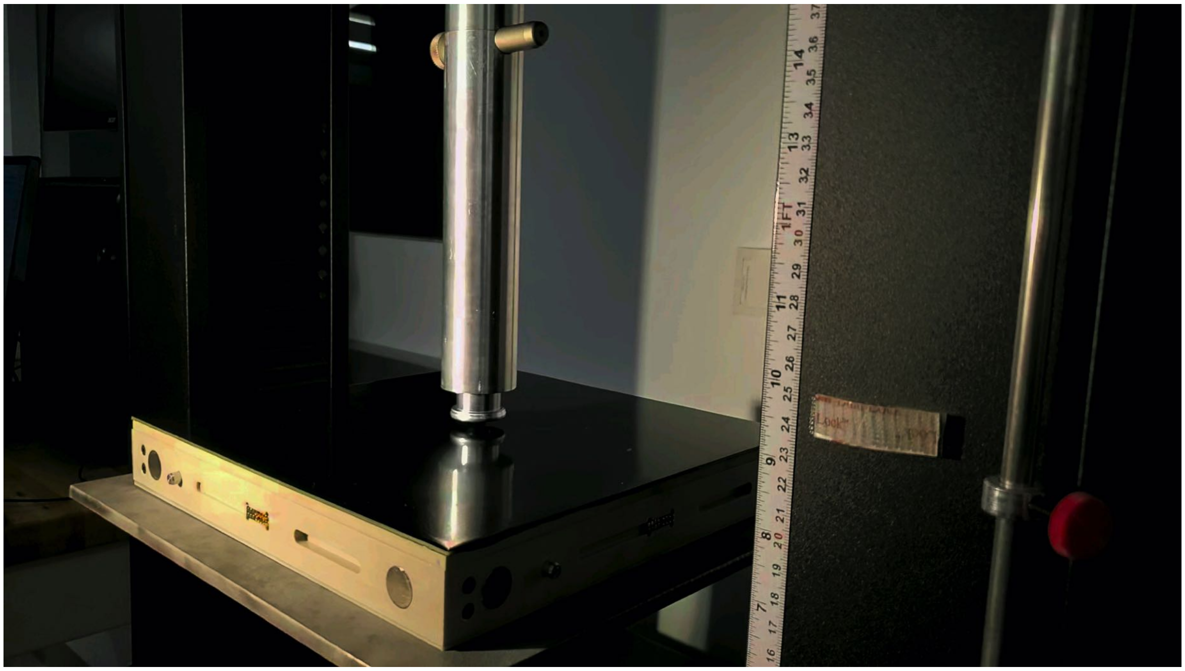
2. After Panel Connection

J. Custom-Built Rigs for Verification Tests

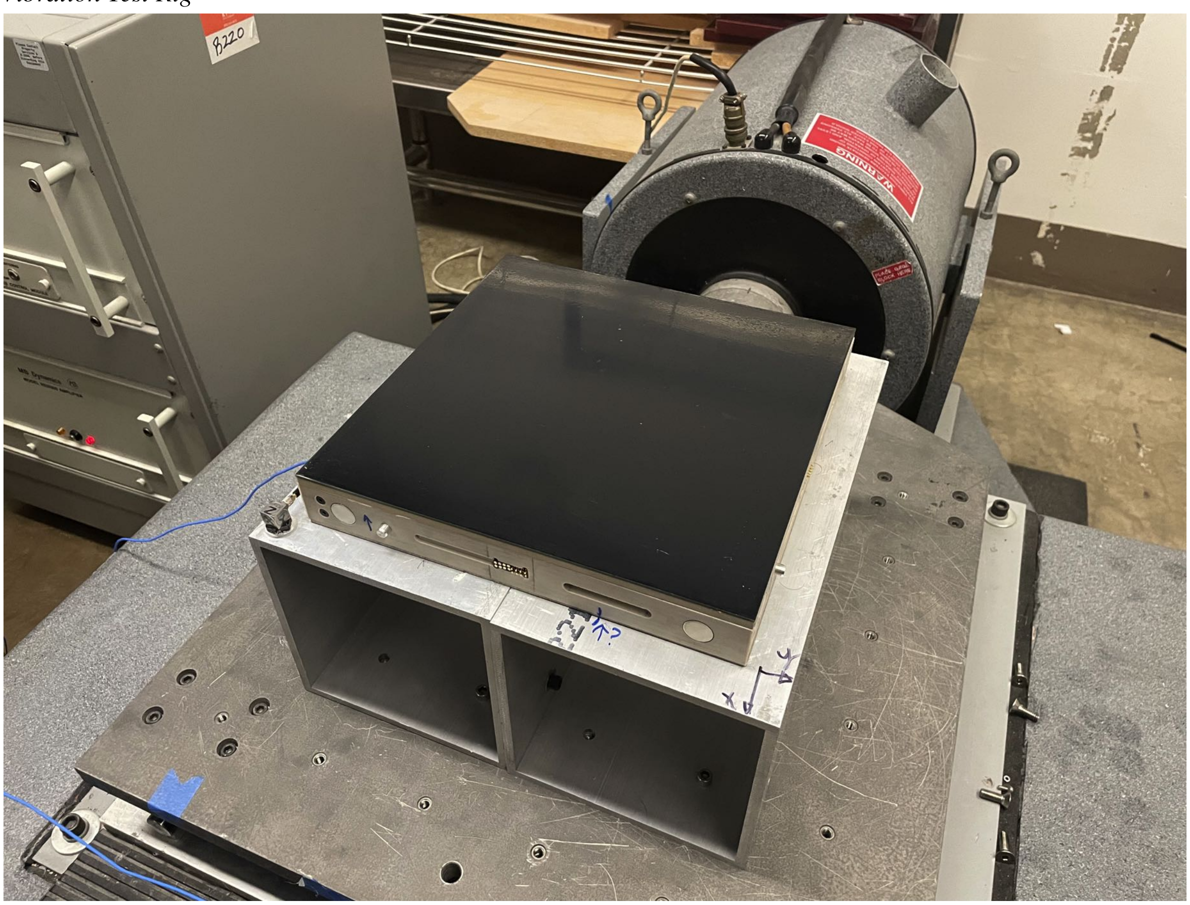
1. Long Term Effectiveness Test Rig



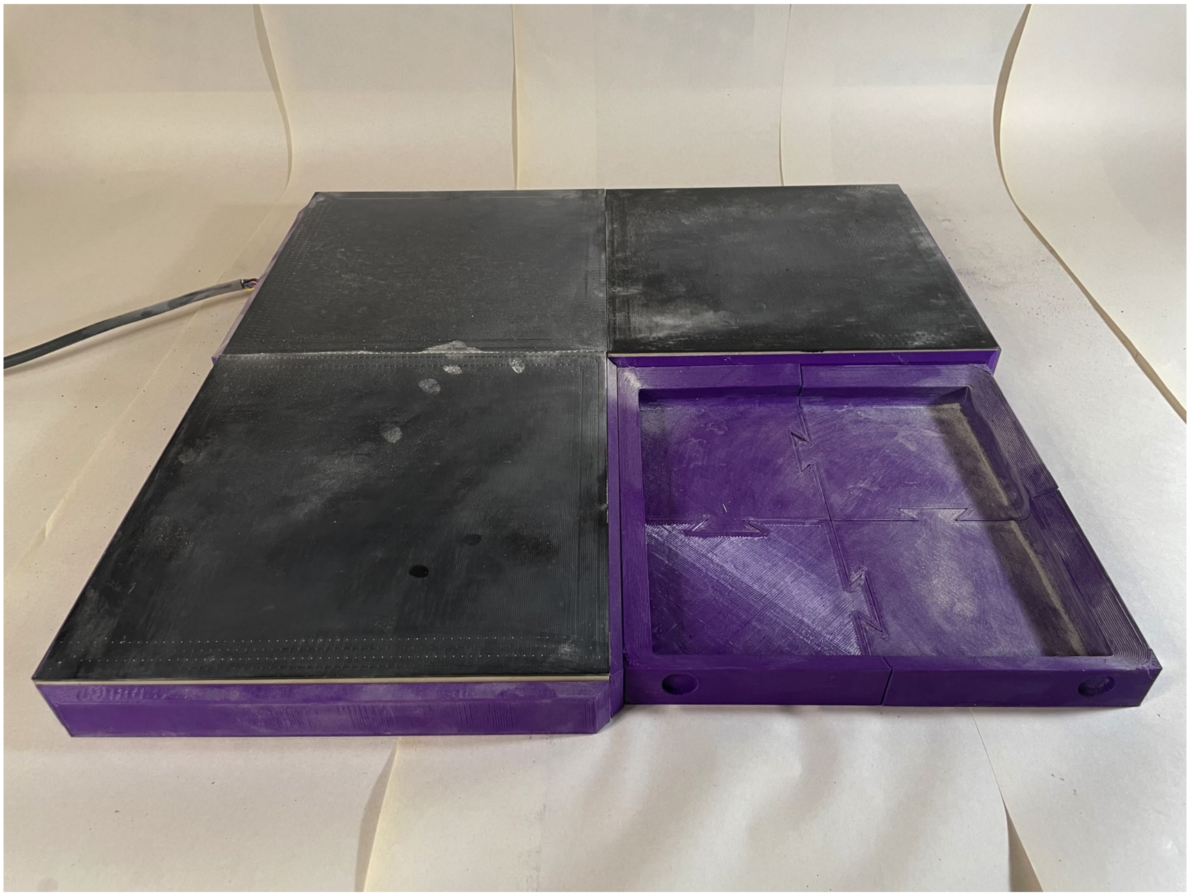
2. *Load Test Rig*



3. *Vibration Test Rig*



4. Full Panel Demonstration



K. HOMES Demonstration

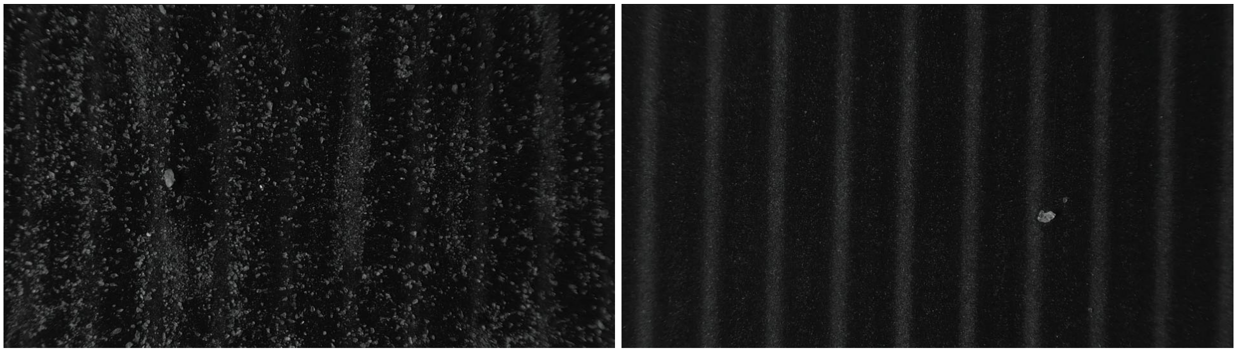


Fig. 35 Fine dust trial

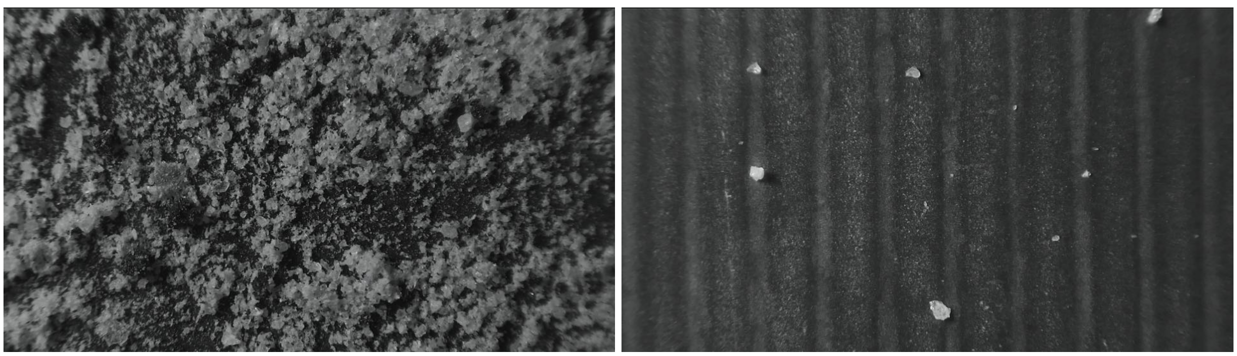


Fig. 36 Coarse dust trial

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