Design and Fabrication of an EDS-Enabled Brush Prototype for Lunar Dust Mitigation

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In past lunar expeditions, surface operations have been impeded by the presence of lunar regolith. The electrostatic nature and small particle size of lunar dust cause adversities such as surface abrasion, vision obstruction, thermal surface degradation, and health issues, necessitating the development of dust mitigation strategies for future lunar surface operations and settlements. This research presents the development of a prototype for a novel approach to lunar dust mitigation, through the integration of an Electrodynamic Dust Shielding (EDS) system into a handheld brushing mechanism. By combining the mechanical action of a brush with the electrostatic repulsion of an EDS system, the design aims to enhance dust removal efficiency and brush longevity while maintaining a compact and robust design suitable for lunar environments. Building on previous research, the prototype features an improved electrode configuration designed to facilitate directed dust movement during, and after, brushing. The prototype manufacturing process incorporates PCB-based electrode integration to ensure structural integrity and reliable electrical performance, along with delivering the required tolerances in electrode spacing, and other specifications, cost-effectively. Testing plans include evaluations of dust removal efficiency under various voltage conditions and assessments of electrode effectiveness during brushing and in clearing debris from bristles. The results from prototype fabrication and planned testing will provide key insights into the effectiveness of dielectrophoretic forces in assisting mechanical dust removal. By evaluating both the functional performance and feasibility of the system, this study aims to establish a foundation for future iterations of EDS-enabled brushes that can be deployed in lunar environments.

I. Nomenclature

EDS = Electrodynamic Dust Shielding
UHV = Ultra High Vacuum $< 1 \times 10^{-6}$ Pa
DEP = Dielectrophoretic (Force)

II. Introduction and Background

Lunar surface operations and observations have suggested the presence of dust layers on the moon. For instance, Apollo astronauts observed a glow on the Lunar horizon, supporting the presence of dust clouds over the Lunar surface [1]. Additionally, observations made by the Lunar Ejecta and Meteorites Experiment (LEAM) [2] also provide evidence that suggests a dust layer over the moon. It has been suggested that this dust is the product of the Lunar surface being electrostatically charged by incident UV radiation or solar wind, leading to levitating particle clouds being present above the surface [3]. Even in the absence of these phenomena, lunar dust clouds would be stirred up by any human or robotic activity on the lunar surface.

A. Challenges

This lunar dust has presented significant obstacles to lunar surface operations, such as those during the Apollo missions. Astronauts reported obscured vision and clogged bearings on EVA suits which impaired movement, so much so that subsequent EVA sessions weren't feasible. Furthermore, this dust created health hazards in the form of dust

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inhalation and pneumoconiosis, with detrimental long term effects on neurons and lung cells [4]. The lunar dust also had a tendency to coat mechanisms and thermal control surfaces, leading to undesirable thermal properties and excessive wear and tear [5]. It is thus crucial to address the mitigation of lunar dust before further Lunar missions or large scale settlements can be attempted.

B. Proposed Solutions

There are a number of solutions that have been proposed to address the issue of lunar dust mitigation. One such solution is the use of simple brushes, to mechanically remove the dust from surfaces. Research carried out on the efficacy of brushing as a lunar dust mitigant for thermal control surfaces, shows that certain materials can remove enough lunar dust to regain 80% of thermal efficiency after 20 strokes, and 90% of thermal efficiency after 200 strokes [6]. This solution has its merits in the nonexistent power requirements, minimal cost, ease of operation, and noncritical failure modes. However, for large surfaces that require consistent maintenance, achieving a 90% removal over the entire surface is rendered an impractical or arduous task when so many strokes are required.

Another solution being developed to deter the buildup of lunar dust on surfaces is the use of EDS (Electrodynamic Dust Shielding) technology. EDS Technology operates with a multi-phase electrode system, that repels particles using the dielectrophoretic force generated by the electrode system's non-uniform electric field. AC current applied across each phase of the electrodes, embedded in a surface, create a "wave-like" motion that pushes particles away from the surface in a common direction [7]. This technology enables effective and autonomous dust removal from a surface. Yet there are still a number of applications where this solution faces drawbacks: since these circuits are embedded into the surface of a system, they increase system complexity and power requirements. Additionally, they are challenging to implement in certain materials or surfaces, and are an expensive system component in structures that are smaller or might only require occasional dust cleaning. The proposed concept outlined in this paper aims to mitigate the drawbacks at the intersection of these two methods, and present the design of an early prototype to cost-effectively test the given concept.

III. Past Work and Proposed Solution

To achieve the target of creating an effective lunar dust mitigation solution for applications not covered by EDS technologies, team "Shoot for the Moon", a Georgia Tech student team, proposed a design for a brush that would use the combined effects of a multi-phase electrode system typical of EDS technology, supplemented by the use of a UV source to electrostatically charge the bristles and provide additional force [8]. While this design wasn't built, it paved the way for work done after the proposal on the development of a simple test article involving a single row of electrodes enmeshed within brush bristles. This article faced some apparent limitations, such as only using a two-phase system and being unable to exert any "brushing" motion due to the thickness and stiffness of the electrodes, as well as the temporary arrangement of the electrodes within the brush. As such, it was a rudimentary proof-of-concept demonstration for the idea's potential.

Following this preliminary test, the design orientation shifted to a brush with integrated EDS for simplified operation, and an active three-phase electrode system for directed dust movement during brushing. This direction of design was met with an initial prototype, shown in **Figure 1**.

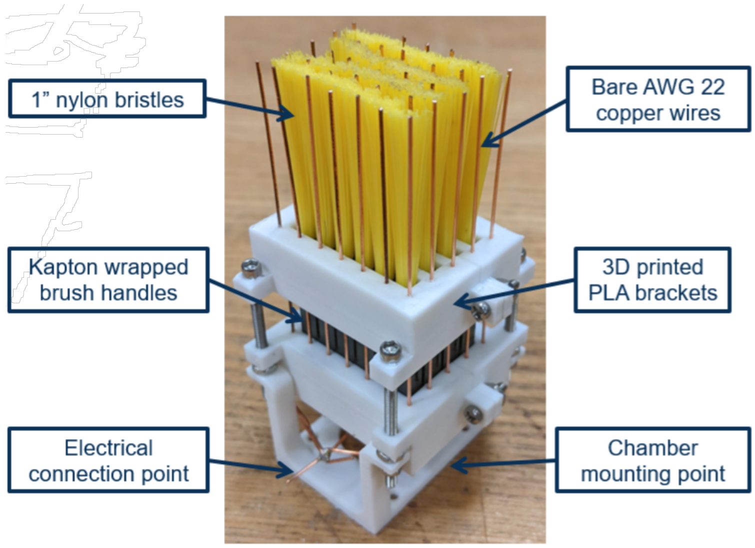

Figure 1: Initial EDS Brush Prototype [7]

This new prototype made the first effort to align the bristles and electrodes to create a system capable of brushing, and upgraded the electrode configuration to the three-phase standard of EDS. It was constructed using a 3D printed frame with a copper wire electrode structure soldered together. The nylon bristles were positioned between the electrode grid to facilitate the testing of lunar simulant removal from the three-phase system.

A. Initial Prototype Evaluation

This was a higher-fidelity prototype, and demonstrated some clear improvements and important design considerations that would need to be addressed in future design iterations and through testing. Unfortunately, this prototype experienced shorting in metal components of the nylon brush handles that were held within the structure, which led to difficulties in electrode testing by limiting operation at higher voltages [9]. Alongside that, the copper wire used in this prototype was inflexible and therefore was unable to be tested during active brushing, as the electrodes could not rebound elastically during the brushing process, and would simply deform. This limited the testing setup and the collection of data on the efficacy or benefits of a three-phase system during brushing.

Brush testing was carried out at varying voltages of $750V_{pp}$ under vacuum. Lunar simulant was applied to the brush and electrode tips, and movement of the simulant away from the electrodes was observed, further facilitated by the EDS causing movement in the bristles. The lunar simulant was observed as having cleared from distances of up to ~1mm from the electrodes. The large inter-electrode spacing in this prototype, about 5mm, meant that the non-uniform electric field could not generate large-enough dielectrophoretic or coulombic forces on the particles to move them into the field of the next electrode. The experiments carried out on this prototype thereby demonstrated that limitations in the manufacturing of the brush and in the area of effect of the electrodes were the main obstacles that needed to be overcome in the development of a second prototype.

B. Future Prototypes

The prototype proposed in this paper is centered around the research, design, and development of an alternative manufacturing method for the EDS brush. The main objectives of this prototype were to address the aspects of previous prototypes that required improvement, such as manufacturing tolerances, electrode efficacy, operational brushing functions, and so on. This prototype would then form the basis of a design that could be used for rapid manufacture, prototyping and testing to provide better insights into the efficacy and practical challenges posed by EDS-Enabled brushing systems.

IV. Defining Design Parameters

From previous prototype iterations, it was clear to see that an EDS-enabled brush prototype would have to satisfy specific design requirements. Logistical goals for this research as a rapid prototyping method were to minimize the cost per prototype, and to maximize the ease of manufacture.

A. Physical Considerations and Constraints

To discuss the design ideology behind the developed prototype, and to better identify design constraints and considerations, it is important to first identify factors that might influence the design of each component of the prototype. The previous prototype was analyzed to determine what basic features the design constitutes, and which improvements should be implemented. The main aspects of the EDS brush are the electrodes/electrical system, the bristles, and the structure that holds them together. Each of these aspects were carefully considered in order to identify how they might impact future iterations in **Table 1**

Prototype Component	Previous Implementation	Considerations
Electrodes	3D Soldered wire grid	• ±0.5mm Tolerance on electrode spacing • Ease of electrode array assembly • Physical shorting/arcing prevention, flexible electrodes
Bristles	Whole brushes between electrodes	• Ensure any conductive metal handles are insulated • Electrodes enmeshed in bristles
Structure	3D Printed and fastened	• Ease of assembly and sufficient insulation to electrodes • Support for bristles/electrodes • Sufficient tolerances for the electrode array

Table 1 Design considerations derived from component manufacturing methods in the initial prototype.

Operationally, this new design also needed to meet additional constraints based on the functions of the system. Most of these considerations occur in the case of the electrodes. They must be fully insulated to prevent Paschen breakdown or shorting, since they will be exposed wires that can come into contact while flexing during brushing. Additionally, the electrode assembly will need to ensure an overlap (or contact) between the area each electrode can clear, to facilitate the wave-like motion of electrical fields that will clear particles from the brush. Just the same, the structural component of the brush would need to be easy to manufacture and assemble when dealing with the numerous electrodes, while providing the required electrical insulation and structural rigidity to enable brushing applications. Lastly the design needs to meet logistical constraints such as minimizing the cost of the prototype, and maximizing the ease/speed of assembly. In order to supplement these constraints with ease of manufacture and the desired properties, the decision was made to redesign the structure of the brush entirely.

B. New Prototype Design

The base of the prototype's design is the implementation of a PCB (Printed Circuit Board) in order to hold and position wire electrodes for the three phase system. The use of a PCB to create the electrode array crucially provides the ability to create and constrain electrode layouts to tight tolerances, which is vital when the inter-electrode spacing needs to be low. Just the same, it also provides ease in terms of procuring and creating multiple boards. The electrodes in this case are simply wires that are soldered in place onto through pads placed on the PCB in the desired layout.

As a corollary, the proposed structure for the prototype of the brush is now built using epoxy resin. This is done in a two-part structure, to clearly delineate the purpose of each layer. The first layer would insulate the PCB, provide protection against shorting, and provide structural rigidity to the electrodes. The second resin layer would then be used to lock in all the bristles, similar to the resin-set manufacturing method used by brush manufacturers. This method then allows for ease in simply requiring a mold to be cast, and minimising assembly beyond the epoxy setup. There are some concerns to note with the use of epoxy in space environments, such as outgassing in vacuum, and in the long term, any thermal effects on the PCB [10]. For the purpose of this prototype, some of these concerns are overlooked. Planned testing conditions for this prototype don't include UHV, as the main objective of this prototype is to proof the brushing concept and provide additional feedback on the manufacturing technique as a whole. An example of the epoxy approach can be seen in **Figure 2**, in a diagram with an early model of the prototype before the PCB approach was finalized:

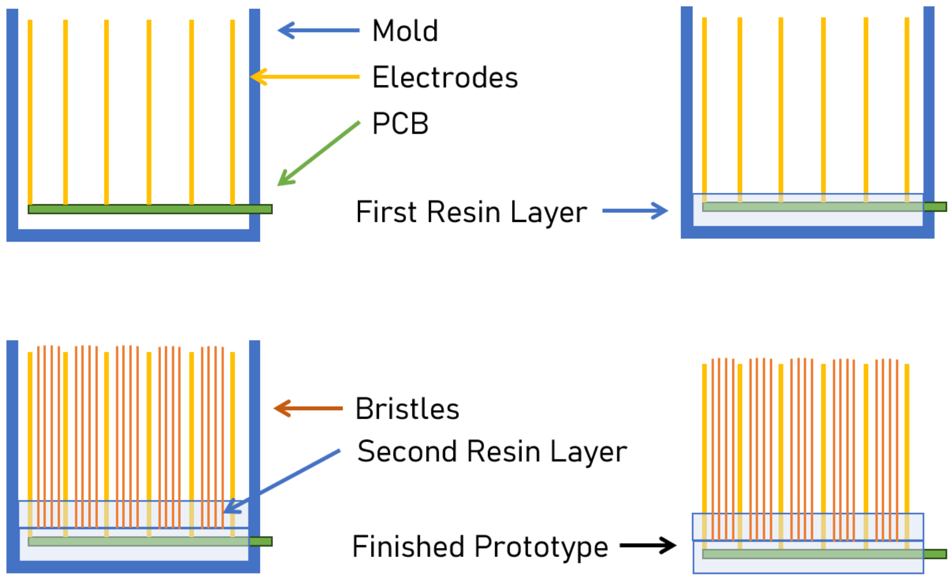

Figure 2: Two layer epoxy approach for PCB and bristles

Lastly, previous bristle integration was done by taking units from commercially available brushes. For this prototype, a brush will be placed in epoxy with the bristle tips submerged, as demonstrated in **Figure 2**. These bristles will then be separated after the resin sets. This allows the bristles to surround the electrodes and more effectively brush dust away, as well as allowing the electrodes to more effectively clear dust from between the bristles. One of the weaknesses of resin-set brushes is their bristle retention. The constant cross-section of the bristles makes bristle detachment a possibility, and so this approach could be strengthened by crimping the base of the bristles to ensure better retention in the epoxy for designs in the long term. In the case of this prototype however, this drawback is also not a concern.

V. Design Development

Development of each aspect of the design based on the determined constraints mainly centers around the PCB and its parameters. There are various aspects of the PCB that need to be determined to provide desired characteristics and performance. These aspects include metrics such as the electrode diameter and electrode spacing, the pad diameter on the electrods, the trace width on the PCBs, and the trace spacing. These parameters should be adjusted to maximise the electric field strength around the electrodes, minimize the voltage required to achieve a given electric field, and to ensure that there is sufficient spacing between the traces, which should have sufficient area to sustain the required voltage/current. There are some constraining values here, such as the size of the electrodes, and the trace/pad spacing, which will be the driving factors in these calculations.

In order to verify the performance of the electrodes at particular , rudimentary calculations were performed to ensure that the given metrics for electrode diameter would be able to provide the sufficient dielectrophoretic/coulombic force to clear lunar dust from its vicinity. This provides us an idea of the expected dynamics of a particle at a specified distance from an electrode, assuming a given electric field strength. With these ballpark values, empirical testing cou be used to better understand the complex electric field interactions, and refine calculations to better reflect the system. For this prototype however, it serves the purpose of validating the system's potential to exert the required forces.

A. Electrode Configuration

The electrode configuration for this prototype is based off a reconfiguration of the three phase system used in the initial brush prototype. This configuration consists of three sets of interdigitated electrodes as a baseline, that would create a linear wave like motion when hooked up to a three phase AC source, pushing dust in one direction and out of the brush.

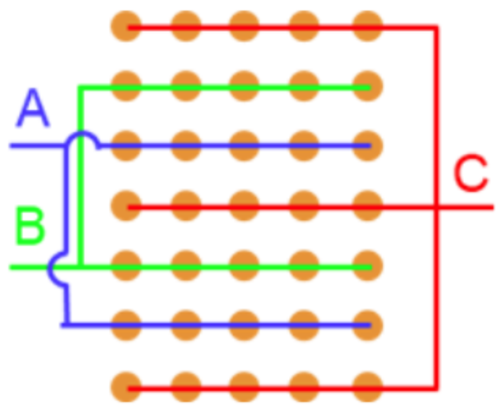

Figure 3: Wiring configuration for initial prototype's 3-phase EDS operation [9]

In order to adapt this electrode configuration to a PCB design, the initial approach taken was to reconfigure the interdigitated electrodes to a single layer PCB by rerouting a single layer, as shown in the mockup in **Figure 4**. This allowed for reduced production costs in theory, but created more issues later on. More importantly, the electrode configuration was updated from the rectilinear grid layout in the initial prototype to an isometric grid layout. This provides a higher packing density of electrodes, and subsequently, better electric field coverage.

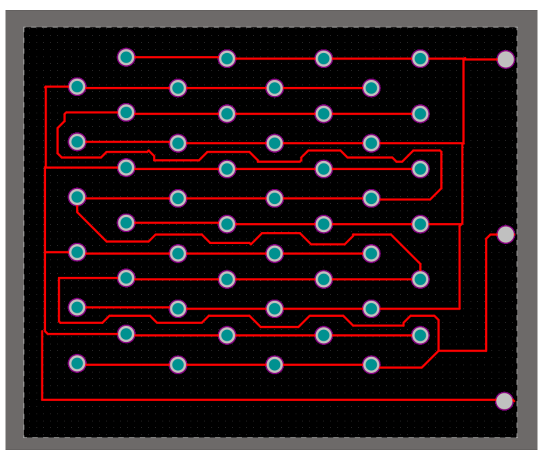

Figure 4: Wiring configuration for a 2 dimensional 3-phase EDS Operation, with an isometric grid

As this PCB was evaluated, it was found that the routing of electrode layers, combined with the increased length of certain wires, violated certain trace spacing rules and would have been an infeasible design. For that reason, the final design for the PCB, with trace and pad spacing designed according to the IPC-2221 standard, was converted into a multilayer PCB. This PCB had one electrode phase per layer, and therefore had better electrical insulation through the PCB's dielectric layers. The multilayer PCB, which is the final design for this prototype, is shown in **Figure 5**.

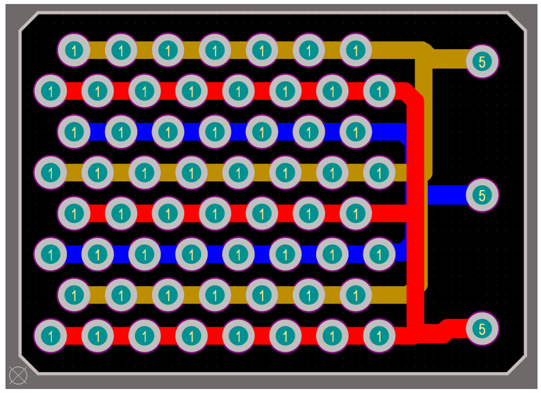

Figure 5: Multilayer PCB Schematic for 3-Phase EDS Operation, with an isometric grid

This layout contains 60 through pads for electrodes to sit in, with three contact pads where each of the three electrode phases can be wired. Each of the phases is shown in a different colour in **Figure 5** for clarity. With the design of this PCB, specifications resulted in a 2mm spacing between electrodes, and a 1mm spacing between pads, which have a 1.3mm inner hole, and a 2.3mm pad diameter. The trace thickness here has been massively increased in order to better transmit the high voltages that are used in a three-phase EDS system.

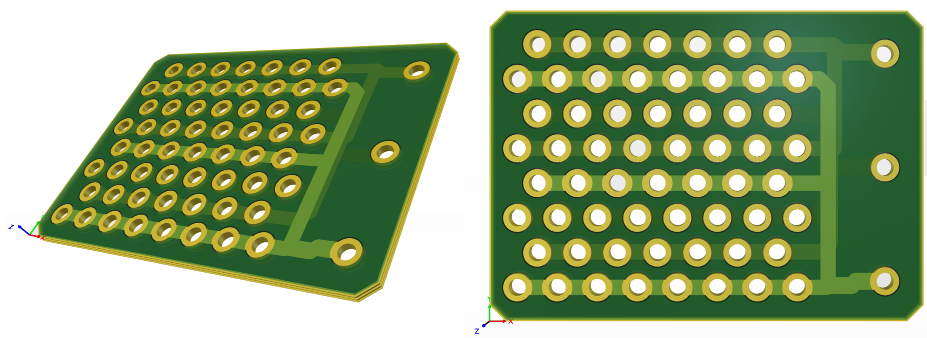

Figure 6: Proposed PCB mockup in Altium

And finally, the prototype electrodes are more clearly evaluated in their material properties and design considerations. One major concern through the use of electrodes during brushing was shorting; as the electrodes flexed, they would have the ability to contact one another, which could cause sparking and electrical breakdown. Since this posits a significant safety risk, a shorting prevention method for the electrodes needed to be determined. The proposed solution for this is in the form of nylon coated wires. Nylon bristles have proven effective in brushing applications on lunar dust [6], and so alongside ease of procurement and fulfilling any requirements that the prototype might have for testing, those were selected as bristle materials, so that the electrodes could possibly provide mechanical brushing function alongside their EDS dust mitigation. Lastly the wire material was considered. Copper wire was used in the initial EDS brush prototype, but did not elastically deflect when pushed up to a surface. This meant that the prototype couldn't be used for brushing, as the electrodes would simply deform, hold their figure, and introduce the risk of shorting. Alternative, springier metals like aluminum or steel were considered, but in the end, a flexible copper wire that allows for the electrodes to deflect without plastic deformation was selected, to ensure that copper's conductive properties would allow the electrodes to generate the strongest electric field possible. A mockup of the final brush can be seen in **Figure 6** and **Figure 7**. In this rudimentary mockup, the electrodes are the yellow upright beams, and the bristles are the orange bristle-like features that surround them. The rectangular layers encasing the PCB at the bottom are epoxy resin, where the lower expoy layer has been made transparent to more clearly show the PCB.

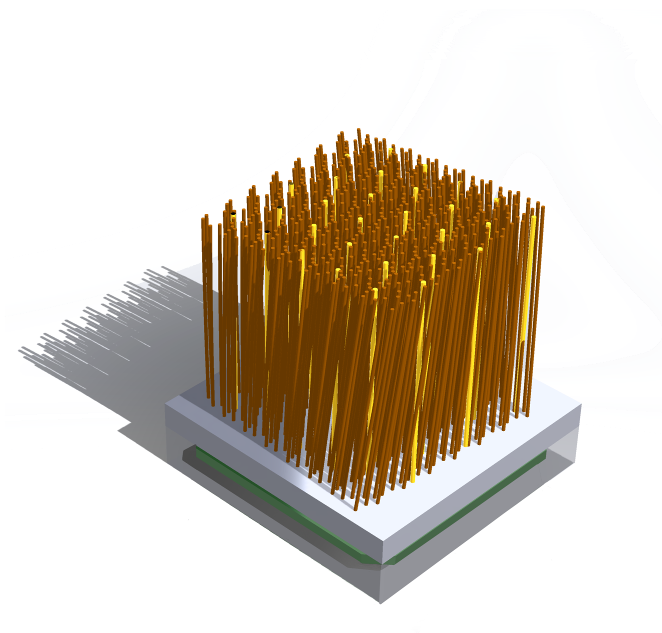

Figure 6: A 3D mockup of the brush design

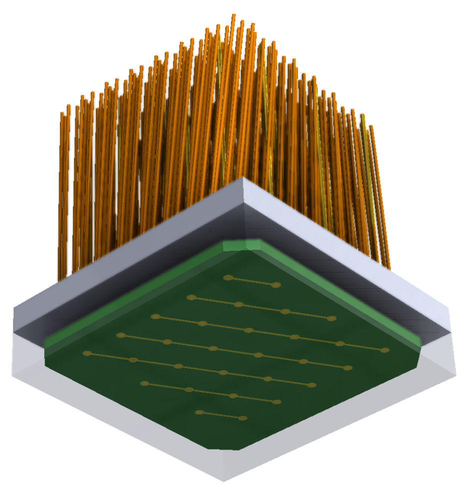

Figure 7: Bottom view of the brush mockup with a visible PCB

Lastly, in the manufacturing plan for this prototype, a mold would be required to pour and set the epoxy for the structural assembly of the board, electrodes, and bristles. The mold will be a simple two part mold, 3d printed for ease of assembly and use. The digital contacts which offer an area for the electrode phases to be operated will hold the PCB above the base within the mold as the first resin layer sets (see **Figure 2**). A nylon brush will then be partially submerged within the brush, and the bristles will be cut off from the brush and trimmed down to size as a final step after the resin sets.

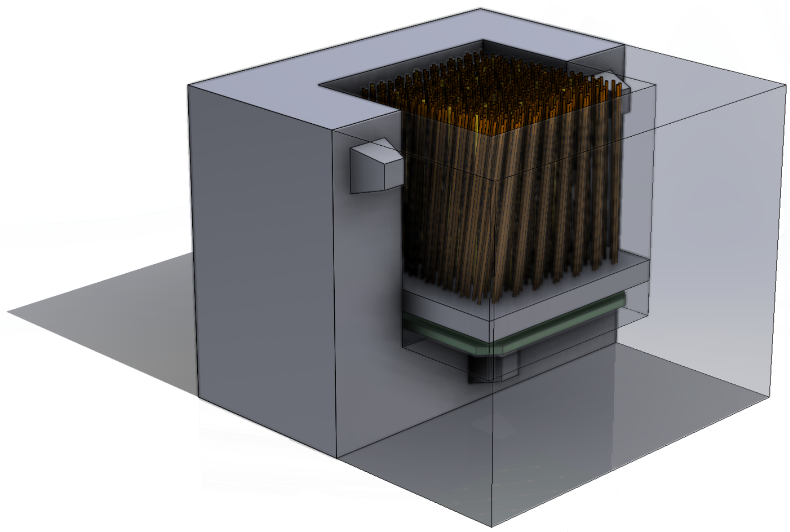

Figure 8: 3D printed mold design with alignment features

VI. Conclusion and Future Work

Overall, the prototype demonstrates strong potential as a streamlined and cost-effective testing article, with the Bill of Materials amounting to only tens of dollars per EDS brush. This affordability enables rapid prototyping and iteration, facilitating data collection and concept validation by assessing the effectiveness of EDS-assisted mechanical brushing in removing lunar dust. The design is particularly promising for dust mitigation applications where traditional EDS surfaces may present engineering challenges, consume excessive power, or be impractical due to flexibility constraints—such as on an astronaut's visor. Current efforts are focused on manufacturing test articles and evaluating their performance and efficacy using lunar simulant in high-vacuum chambers. The results of these tests will provide critical data for refining this tool, developing a means of helping lunar settlers mitigate the persistent challenge of lunar dust.

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References

[1] Gold, T., and Williams, G. J., "Electrostatic Transportation of Dust on the Moon," *Photon and Particle Interactions with Surfaces in Space*, edited by R. J. L. Grard, Springer Netherlands, Dordrecht, 1973, pp. 557–560.

[2] Zook, H. A., and McCoy, J. E., "Large scale lunar horizon glow and a high altitude lunar dust exosphere," *Geophys. Res. Lett.*, Vol. 18, No. 11, 1991, pp. 2117–2120.

[3] Walch, B., Horanyi, M., and Robertson, S., "Electrostatic charging of lunar dust," *AIP Conference Proceedings*, AIP, 1998.

[4] Caston, R., Luc, K., Hendrix, D., Hurowitz, J. A., and Demple, B., "Assessing toxicity and nuclear and mitochondrial DNA damage caused by exposure of mammalian cells to lunar regolith simulants," *GeoHealth*, Vol. 2, No. 4, 2018, pp. 139–148.

[5] Gaier, J. R., "The Effects of Lunar Dust on EVA Systems During the Apollo Missions," Technical Memorandum (TM) NASA/TM-2005-213610, NASA Glenn Research Center, 2005.

[6] Gaier, J. R., Journey, K., Christopher, S., and Davis, S., "Evaluation of Brushing as a Lunar Dust Mitigation Strategy for Thermal Control Surfaces," Technical Memorandum (TM) NASA/TM-2011-217231, NASA Glenn Research Center, 2011.

[7] Johansen, M. R., "History and flight development of the electrodynamic dust shield," *AIAA SPACE 2015 Conference and Exposition*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2015.

[8] Liu, Z. S., Mahmud, A. S., Sjolund, K. G., et al., "Hybrid Dust Mitigation Brush Utilizing EDS and UV Technologies," Tech. rep., Georgia Institute of Technology, 2021. Available: `https://bigidea.nianet.org/wp-content/uploads/GeorgiaTech-Final-Technical-Paper-2021-BIG-Idea.pdf`.

[9] Sjolund, K. G., Shaible, M. J., Orlando, T. M., and Linsey, J. S., "Development of an Electrodynamic Dust Shielding Enabled Brush," *NASA Exploration Science Forum (NESF)*, Georgia Institute of Technology, 2023.

[10] Pastore, R., Delfini, A., Albano, M., Vricella, A., Marchetti, M., Santoni, F., and Piergentili, F., "Outgassing effect in polymeric composites exposed to space environment thermal-vacuum conditions," *Acta Astronautica*, Vol. 170, 2020, pp. 466–471. https://doi.org/https://doi.org/10.1016/j.actaastro.2020.02.019, URL https://www.sciencedirect.com/science/article/pii/S0094576520300813.