Lunar Dust: Its Impact on Hardware and Mitigation Technologies

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Abstract

The finest fraction of Lunar regolith – Lunar dust – has been proven to pose a challenge for surface hardware operations. This paper discusses the impact of Lunar dust particles on various hardware and explains the reasons for such negative influence in order to better understand possible solutions. This work focuses on presenting a classification of viable dust mitigation methods and examples of such technologies. A variety of approaches from active, passive, and implicit dust mitigation solutions are presented to showcase and evaluate available technologies for design engineers working on Lunar hardware.

Introduction

NASA and its international partners are planning to land astronauts on the Lunar surface during the Artemis program. In the Apollo missions, one of the factors heavily affecting Lunar operations was Lunar dust, or regolith [1]. In the words of Apollo 17's mission commander Eugene Cernan in 1973, "…dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome every other physiological or physical or mechanical problems, except dust…" [2]. In this paper we present and analyze some solutions available to fight the Lunar dust problem.

During the Apollo program, researchers discovered negative effects of Lunar dust on almost all equipment it came in contact with [1]. Dirty or scratched surfaces (helmets' visors, thermal surfaces, etc.), mechanisms jammed with the dust (astronaut suits, the Lunar rover, the geological tools, mechanisms of cameras). All of these challenges interfered with the astronauts' work, compounding the difficulty and physical demand of operating in an EVA. Outside of the scope of this paper, it is equally important to mention how exposure to Lunar regolith (e.g., if brought into the habitat) also represents a health hazard for astronauts, impacting their respiratory, cardiovascular, nervous and ocular functions [3].

There are multiple ways that dust can damage a piece of hardware. The first type is dust entering the gaps between elements in rigid-body mechanisms. Such intrusion, due to the characteristics of the regolith, described further in the next section, increases the friction of kinematic pairs and, in some cases, can jam them completely. The traditional approach is to seal the joints from the dusty environment. However, as Apollo's experience showed, the abrasive characteristics of the Lunar dust tend to break seals [1]. This means that traditional seals are prone to damage and are possibly only postponing the inevitable friction increase in the protected kinematic pairs. Dust abrasion also has a negative effect on surfaces that are expected to remain smooth, e.g., spacesuits' visors, solar panels, thermal coatings, sensors' surfaces, etc [4]. Thermal surfaces can be degraded by dust, not only through abrasion but also by dust accumulation as it modifies the thermal emissivity and/or the effective surface of exposure [2]. Finally, conductive elements can be severely damaged by destructive dielectric discharge of the accumulated electric charge, including sensitive microelectronic components. As demonstrated, the mechanisms of dust-related damage differ greatly, and therefore demand bespoke solutions for the challenge of dust mitigation.

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The Lunar Environment and Dust Characteristics

Lunar regolith is the layer of unconsolidated material covering almost the entire surface of the Moon. Even though it also includes larger pebbles, rocks and boulders, this work focuses on the hardware impact from subcentimeter fractions of the regolith. This grey sand-like material is composed of a heterogenous mix of rock fragments, minerals, glass, and glass bonded agregates called agglutinates [5]. The lunar soil is very fine and therefore sometimes referred to as "dust". Representative samples show a median particle size between 40 µm and 130 µm, and with particles smaller than 20 µm representing 10% to 20% of the weight [6]. In addition, some of the most abundant minerals such as arnorthite, bytownite, labradorite, fayalite or forsterite exhibit Mohs hardness values of 6 or above, making them harder than common engineering materials (e.g., aluminium alloys, titanium alloys, stainless steel). Furthermore, these minerals, together with glass, form grains with sharp and serrated edges due to their brittle nature, and are most present in the smallest size fractions [7], which explains the abrasive nature of the dust. Additionaly, due to constant solar wind plasma bombing, cosmic ray spallation, solar UV, and X-ray radiation, the dust is also electrostatically charged. Certain characteristics of the Lunar environment and regolith (discussed later in this section) lead to a large build-up and retention of charge. This build-up of charge causes particles to adhere easily to surfaces and may also cause the dust to float above the surface having easier access to mission hardware. This carries a significant risk to most hardware.

Further charging of Lunar regolith can also occur as a result of contact, which will be prevalent when it comes to Lunar surface hardware. This method of contact charging is referred to as triboelectric charging.

If two conducting materials are in contact, charge is transferred between them based on their work function difference. A metal's work function is the energy required to liberate an electron from its surface. The transfer of charge under contact serves to change the material's work functions and bring them into alignment, effectively equalizing the surface potentials of the two materials. Insulating materials do not have work functions, as they by definition do not have free electrons at their surface. It has been found however that insulators in contact with metals exhibit charge transfer proportional to the work function of the contacting metal [8,9]. This dependence on metal work function implies that an 'effective' work function can be assigned to an insulator, which can help determine the direction and magnitude of triboelectric charge transfer for that material. It is important to note however that the effective work function of an insulator is not the same as the work function of a metal. The effective work function simply describes the affinity of an insulator to transfer charge when contacted against metal and is likely determined by a number of factors from hydrophobicity to surface state defects.

When a particle is charged triboelectrically against a conducting surface, it has been shown that the resultant surface charge density is inversely proportional to the particle's size [10]. This relationship means that smaller dust particles in the Lunar regolith will charge to a very high charge-to-mass ratio (specific charge). The larger specific charge of dust particles compounds the dust adhesion problem for Lunar exploration, making it more difficult to prevent adhesion and/or remove adhered particles.

There are two primary mechanisms for the discharge of materials; these are the conduction of surface charge and electrical breakdown of the surrounding medium. Strong electric fields created by charge build-up can lead to electrical breakdown and thus discharging of the charged surface. The breakdown limit in the air is further decreased when humidity is higher [11]. As the Lunar environment is a high vacuum, an electrical breakdown is unlikely to occur. This means that much greater charges can be reached in the Lunar environment relative to in an atmosphere such as the Earth's.

Metals will quickly discharge when contacting a grounded surface. Insulators, however, will not tend to lose charge under the same circumstances, and may even gain extra charge depending on the material. Both metals and insulators can passively lose charge over time to the air surrounding them. Since the lunar environment is lacking suitable atmosphere this mechanism of discharge will not occur. This means that dusty regolith which gains charge, be it through environmental effects or physical interaction, will retain that charge over very large timeframes. Therefore, the only way to remove unwanted charges would be to triboelectrically charge the dust on a material with a similar work function or to introduce it to an atmosphere (i.e., inside of the Lunar module) and use a method such as an ionizing gun.

Classification of Dust Mitigation Methods

To date, there is no single available dust mitigation technique that shows 100% efficacy on all grain sizes and for all possible hardware applications. We agree with the literature suggesting that the Lunar dust problems need to be addressed using multiple dust mitigation solutions combined in a layered engineering defense strategy [12]. In this section, a classification of available dust mitigation technologies is presented.

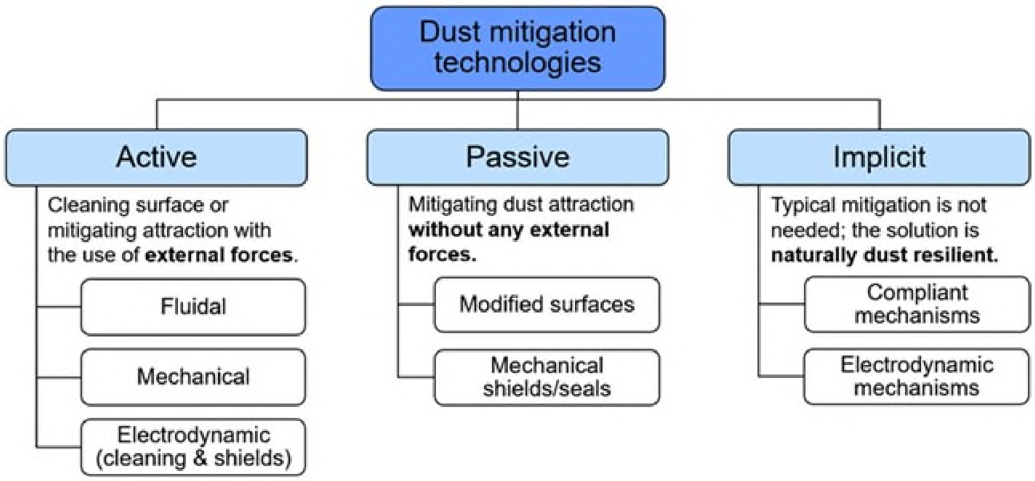

Figure 1. Dust mitigation technologies classification

There are three main approaches to dust protection: active, passive, and implicit – see Figure 1. Active methods are defined by their ability to clean (or sometimes protect – like electrodynamic solutions) surfaces with external force. The external force can be mechanical like in the case of using brushes to dust off surfaces. It can also be any other type of force like such as more advanced electrostatic, magnetic, and vibrational forces. It is important to note that the Lunar dust adhesion is mostly caused by the electrostatic potential gradient, and not by Van der Waals forces which usually play a big role with adhesion. Due to this fact, active methods show different efficacy depending on the attraction forces they target, as such mechanical methods (e.g., brushes) have a low efficacy since they do not break the electrostatic forces between particles. During the Apollo program, brushes were a primary method of cleaning equipment from dust [4]. When used in vacuum they were innefective. Once the equipment was in a pressurized Lunar module, the dust was easier to brush off due to the fact that the atmosphere helps it to discharge [1]. The active group also includes methods that use electrodynamic or vibrating systems. Most active methods focus on removing a dust coating that has already accumulated on a surface. As opposed to that, passive dust mitigation methods decrease dust adhesion or exposure to reduce the contamination before it happens and without the need for any external force. Such methods include sealing and mechanical shielding technologies as well as surface engineering and coatings. Similar to active methods, the efficacy of the types of these solutions differ. For example, microstructured surfaces target Van der Waals forces and present lower efficacy than solutions aiming to minimize the difference in potentials between the Lunar dust particles and equipment surfaces – e.g., work function matching coatings [4]. The last group -the implicit solutions- are designs that, by their nature, are not dust sensitive – e.g., friction-free solutions like compliant mechanisms. Solutions from this group, even when exposed to dust contamination are not affected by it and preserve their functions. This group also includes the usage of mechanisms that are included in active technologies, but as mechanisms themselves – e.g., an electrodynamic system can be used for transporting, size-sorting, and sampling of the dust. Such an approach could potentially be applicable for magnetic and vibrational methods as well.

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Compliant Mechanisms

In this section, we discuss compliant mechanisms as an alternative to traditional rigid-body mechanisms. Dusty environments are quite challenging for rigid-body mechanisms, specifically for the kinematic pairs connecting their components. Sliders leave exposed areas prone to dust contamination which leads to jamming. Hinges are less exposed than sliders but unfortunately can still get contaminated as hinges have gaps that can be penetrated by fine dust. It should be considered to avoid both of them (where possible), especially if other types of protection are hard to achieve. The alternative to mechanisms based on rigid-body kinematic pairs is the use of compliant mechanisms. There is a general rule related to mechanisms that some mechanisms designers refer to, and it says: “prefer pivots to sliders, flexures to either” [13]. This rule may be highly applicable on the Moon to make sure the hardware is dust resilient.

Rigid body mechanisms perform their functions by the relative motion of separate components connected by kinematic pairs. Compliant mechanisms provide motion by elastic deformation [14,15]. As such, they can be designed as monolithic pieces – see an example of compliant hinges compared to rigid body hinge in Figure 2. When designed this way, compliant mechanisms require little to no assembly. Since compliant mechanisms deflect elastically, the work supplied to a compliant mechanism is partially stored as elastic energy in the material of the mechanism. In this sense, they are spring-loaded mechanisms. Once the input force is removed the mechanism releases stored energy and returns to its original shape.

Figure 2. Left: rigid-body hinge; middle: butterfly design of compliant hinge; right: cartwheel compliant hinge

The lack of inter-element gaps in compliant mechanisms eliminates backlash and makes them well-suited for high-precision applications. It also makes them naturally dust resilient by eliminating the gaps prone to dust intrusion, and by eliminating friction between relative moving components. As opposed to rigid-body mechanisms, compliant mechanisms do not require any additional dust protection and therefore using compliant mechanisms can be considered a design level dust mitigation approach which is classified as implicit method, Figure 1. This approach might not be useful for every type of hardware, e.g., applications that require multiple revolutions have to be designed in the traditional way. With compliant mechanisms, the range of motion is also highly dependent on their designs. For example, cartwheel compliant hinge and butterfly hinge, visible in Figure 2, are usually designed to deflect ±20 deg. [16,17]. Designs capable of more significant revolution with up to ±90 deg. are presented in Figure 3. Compliant revolute joints could be used instead of hinges in applications where multiple revolutions are not needed.

Figure 3. Compliant revolut joints; left: Flex-16, right: cross-axis flexure, designed at BYU [18]

Designing compliant mechanisms as whole systems can be more challenging than designing traditional mechanisms and requires careful material and geometry selection to fulfill the kinematic requirements. Nonetheless, there are some standardized analytical designing methods like Rigid-Body Replacement Method or Freedom And Constraint Topology (FACT) as well as numerical methods like topology optimization. An example of a compliant gripper designed by using topology optimization is presented in Figure 4.

Figure 4. 3D printed compliant gripper from opened (on the left) to closed (on the right) position.

Electrostatic Mitigation Systems

Electrostatic mitigation systems consist of high-voltage amplifiers with an electric circuit and electrodes which cover cleaning-target surfaces. The power supply unit applies several types of high-voltage waveforms on the electrodes, generating electrostatic fields nearby to remove charged dust particles. Since electrostatic systems do not require any mechanical drives nor intermediate fluid for handling regolith particles, they have several advantages for use in Lunar and Martian environments, such as simple and low-weight design, low power-consumption and heat-generation, and high dust tolerance. Here, we present some promising techniques that have been developed.

<u>Electrodynamic Dust Shield</u>

Electrodynamic active dust mitigation technologies appear today as the most promising solutions in terms of dust removal efficiency. The most efficient electrodynamic technology existing up to now is the Electrodynamic Dust Shield system (EDS). This concept was mentioned in Tatom's report of NASA [19] but was not manufactured. The first prototype was developed in 1970 by Masuda's group (*University of Tokyo*) [20], initially as a solution for the confinement and transportation of charged aerosol clouds [21]. Since then, many applications have been developed to clean dust in space environments as well as on Earth, e.g., cleaning spacesuits and optical lenses on the Moon, and cleaning solar panels in desert areas [22-29].

The EDS system is based on the electrodynamic field generated by parallel electrodes activating alternately in a sweeping motion. This technology consists of a set of parallel conductive electrodes integrated onto a substrate; each electrode is linked to one of multiple independent power channels. Those channels are driven by a microcontroller which sends a high-voltage (1 kV to 5 kV), alternating current, multiple-phase sequenced signal to each of those electrodes. The electrostatic field generated around each electrode serves as carrier for the dust particles – whether they are charged (positively or negatively) or not, in a sweeping motion, thanks to the alternating nature of the current and the sequenced signal. The general operation of an EDS system is described in Figure 5 [26].

Several methods can be employed to integrate the electrodes on the substrate. The most straightforward one is to make use of a commercial polyamide or PCB board, on which copper electrodes are printed. This allows for quick prototyping, as well as reliably precise manufacturing and integration onto already existing systems.

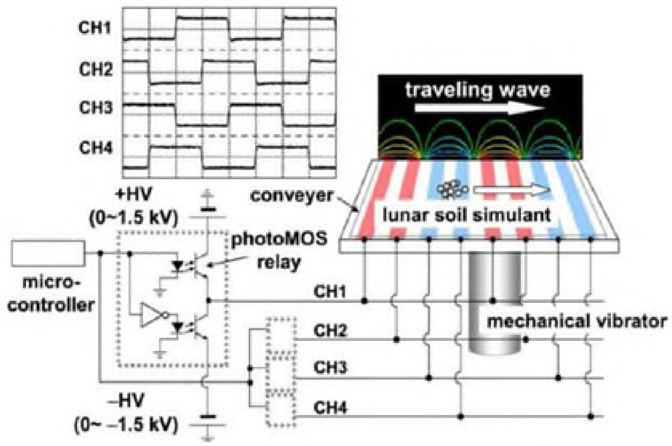

Figure 5. Diagram of the general operation of an EDS system [26]

This technology was originally proposed for dust mitigation operation on rigid surfaces, especially radiators or solar panels, on which the coverage of dust particles has a significant impact. For this particular application, the use of transparent Indium Tin Oxide (ITO) substrates have been suggested. Kawamoto's group [26] reported cleaning rates of Lunar dust simulant ranging from 80% to 90% in air conditions and almost 100% removal in high vacuum conditions. Calle's group [30] also reported cleaning rates ranging from 75%-90%. They further demonstrated the efficiency of the technology by implementing a 20x25 cm EDS substrate on the exterior wall of a Lunar Habitat Demonstration Unit [31].

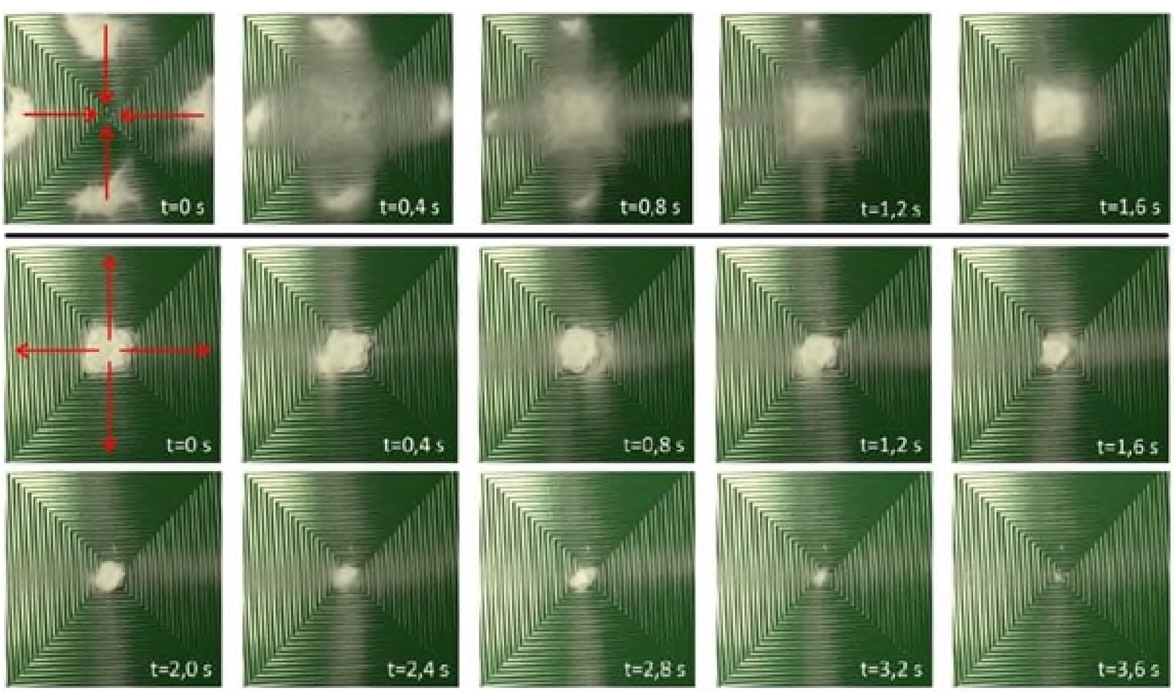

Figure 6. EDS system in 2 different modes of operation. Copper electrodes on PCB substrate, spacing between electrodes = 1 mm, travelling wave frequency = 20 Hz, operating voltage = 2000 V

Figure 6 displays the results of two different sets of qualitative experiments conducted with polyamide powder particles with a particle size distribution of 50 to 100µm. These pictures are successive frames of two different videos: in the first row, the electrostatic travelling wave is pointing inwards; in the second to third row, it is pointing outwards. It is possible to observe the effective displacement of the powder in both cases within a few seconds, even with an important initial dust load.

The EDS technology has recently benefited from development of advanced materials manufacturing, specifically in the domain of spinnable carbon nanotubes (CNTs), allowing the production of "endless" linear networks of CNTs. Originally, the EDS integrated to a spacesuit was developed by Kawamoto [32]. Copper electrodes were then considered because of copper's superior conductivity (16.78 nΩ·m at 20°C, IACS data). The first use of CNTs as electrodes for an EDS system has been proposed by Manyapu [33], under the name SPIcDER (for Spacesuit Integrated CNT Dust Ejection/Removal system). This choice stems from the observation that CNT yarns, although less conductive than most metals, are able to conduct electricity to the point where it generates an electric field that is powerful enough to operate an EDS system; albeit slightly less conductive (1-2 orders of magnitude less than copper), they present a far higher flexibility and mechanical strength (resistance in fatigue), as well as a much lower density, allowing for a reduced weight when integrated to the spacesuit. This combination of factors makes them a better candidate when it comes to integrate the EDS technology to any sort of flexible, mobile piece of equipment requiring dust mitigation when operated on the Lunar surface, including Lunar exploration spacesuits.

CNT yarns as electrodes have proven to be almost as effective as copper electrodes, with similar dust removal rates under the same operating conditions (Figure 7a). However, the use of a flexible substrate brings forward a new set of challenges and limitations, amongst which dielectric breakdown occuring at high operating voltages between neighbouring electrodes (Figure 7b). This phenomenon is, as of today, the main limitating factor for a standardised use on relevant systems. While working well under high vacuum (<100 mPa), using this technology in Earth atmosphere (10^5 Pa) and low-to-medium vacuum is difficult. Research on ways of mitigating the electric arc generation is ongoing, and has already brought forward solutions such as polymer encasing of the electrodes and conductivity enhancement of the material through ionic doping and densification of the CNT structure [34]. The adaptation of the EDS technology to flexible substrates is an active research topic, and it is a safe bet that it will one day be implemented by space agencies in Lunar exploration spacesuits and Lunar dust-sensitive equipment.

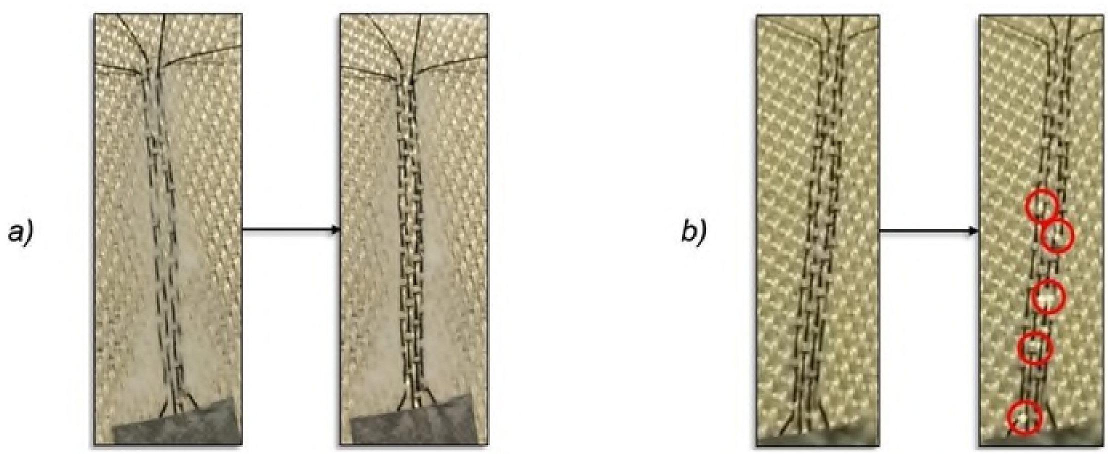

Figure 7. a) CNT EDS sample sweeping Ø60µm PMMA microparticles away with ~100% efficiency at 1200V; b) Dielectric breakdown arcing occurring between uninsulated CNT electrodes at 2000V

<u>Other Electrostatic Mitigation Systems</u>

The electrostatic dust shield system was invented to prevent the Lunar regolith from intruding into a mechanical gap of extravehicular equipment [35] (Figure 8). The system utilizes a standing wave of high voltage applied to electrodes attached to the mechanical gap. The generated electrostatic field can attract particles close to the gap and then repel them outward. The performance of the electrostatic dust shield was evaluated in the lab experiments, and it was confirmed that the system can remove a majority of the particles, approximately 90% of them, compared with the case when they get inside of the gap with no countermeasure (Figure 9).

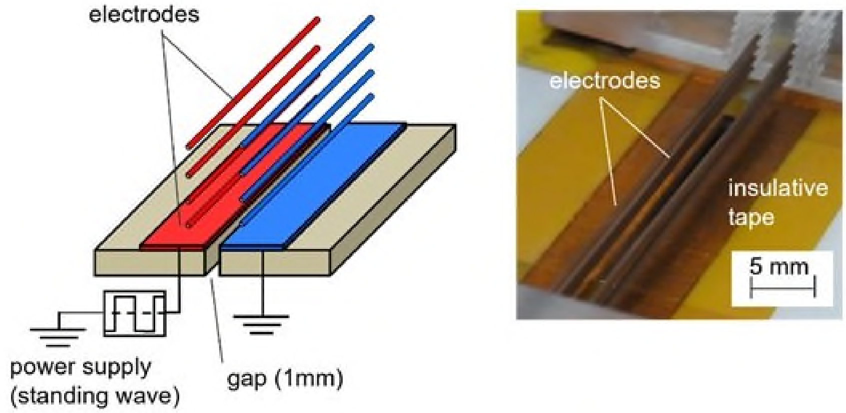

Figure 8. Configuration of the electrostatic dust shield system. Wire and plate electrodes are placed just above a gap. A standing wave of high voltage is applied to electrodes on one side, while other electrodes are grounded, generating an electrostatic field to capture and repel dust particles

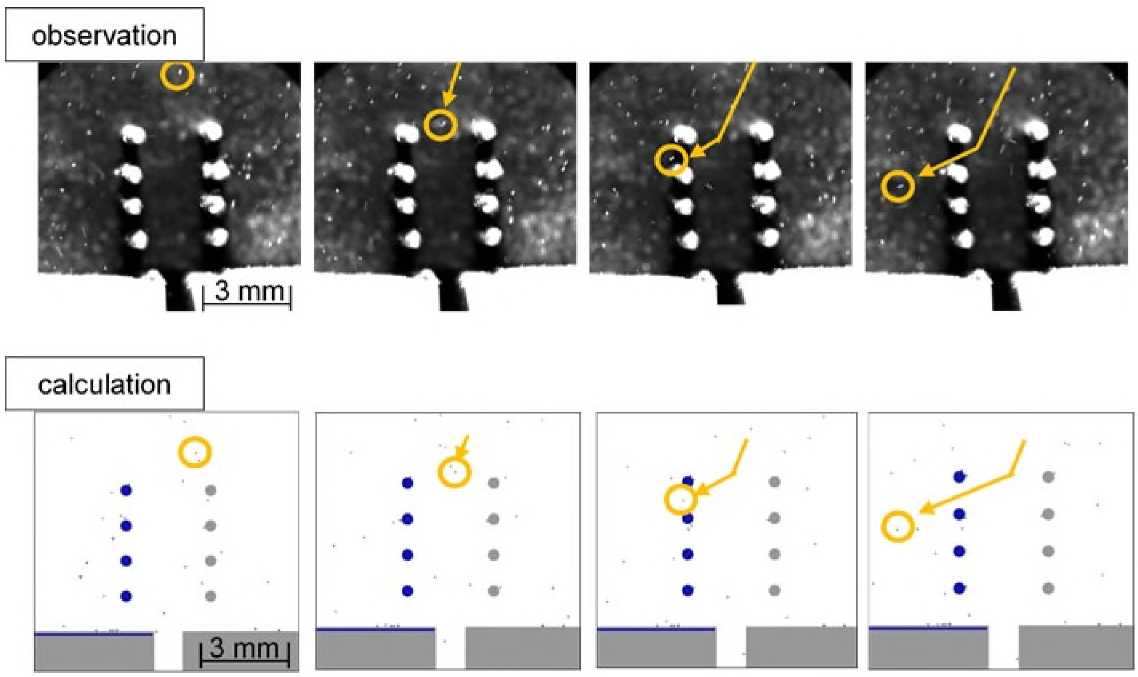

Figure 9. Observed and simulated motions of particles that are supplied to the electrostatic dust shield system from the top. The falling particles are captured and then repelled outwards by the electrostatic force [36]

In addition to the EDS system for spacesuit, a handheld cleaning tool using an electrostatic force was developed for assisting astronaut's cleaning tasks [35]. The tool consists of screen electrodes, a tube with printed parallel electrodes, and a collection bag, as shown in Figure 10. When a standing wave of high voltage is applied to the screen electrodes, the resultant electrostatic field captures the dust on spacesuits, and then the particles are transported to the collection bag by a traveling wave applied to the parallel electrodes. Astronauts can use this device inside or outside of Lunar bases easily and quickly for cleaning spacesuits and even other systems. Figure 11 shows the technology demonstrator.

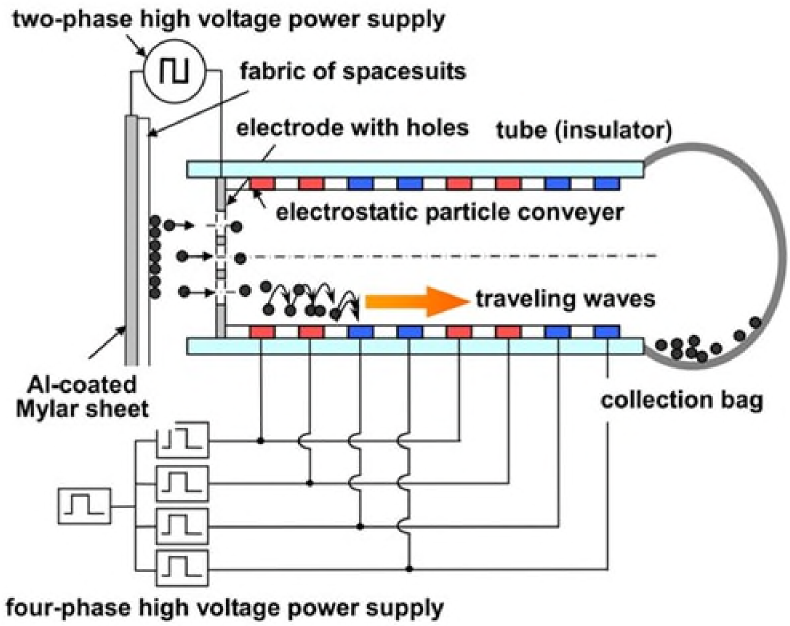

Figure 10. Configuration of the electrostatic handheld cleaning tool for spacesuits. A standing wave of high voltage is applied to screen electrodes, capturing the dust on spacesuits. The captured particles are transported by a traveling wave supplied to electrodes printed on a tube [35].

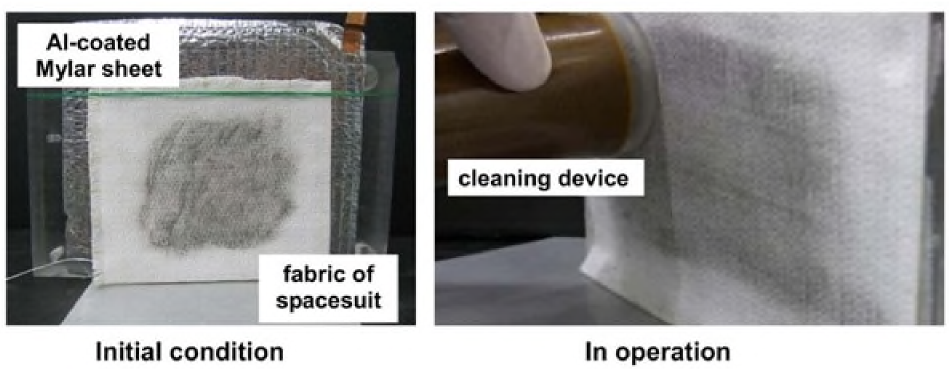

Figure 11. Demonstration of the electrostatic handheld cleaning tool for spacesuits. Astronauts can use this device for quick cleaning for themselves [36].

Moreover, such mechanisms using an electrostatic force for cleaning can also be applied for handling particles as an implicit method. The capturing process of the electrostatic handheld cleaning tool can be used for sampling of the regolith. As shown in Figure 12, the Lunar regolith simulant can be sampled by using an electrostatic force in low gravity environment [37,38]. Another example is the electrostatic size-sorting system [39] (Figure 13). When the regolith simulant particles are transported by using an electrostatic traveling wave, the particles can be sorted by employing a balance between the electrostatic and gravitational forces, which corresponds particle size. The demonstration showed that particles less than 20 μm in diameter can be sorted from the bulk of the regolith simulant efficiently.

While some examples of electrostatic mitigation systems and implicit handling techniques are introduced here, other non-mechanical mitigation systems are also available, such as magnetic, vibration, and the mixing of methods [32,40,41]. Since they also do not rely on mechanical drives nor fluid, the same advantages as electrostatic systems can be achieved for the magnetic and vibration methods.

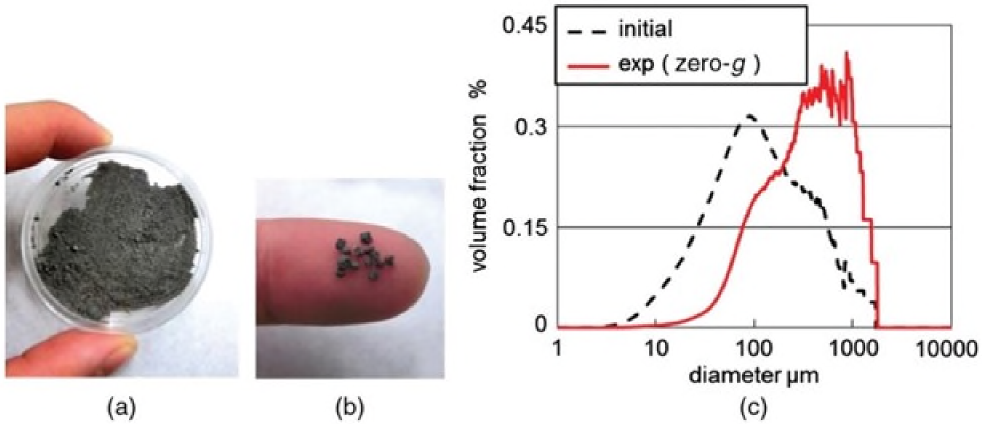

Figure 12. Sampled Lunar regolith simulants using an electrostatic force. (a) (b) approximately 900 mg of the simulant can be collected in one low-gravity experiment. (c) size distributions of initial and captured particles, showing that the electrostatic force can manipulate even larger particles in low gravity [37].

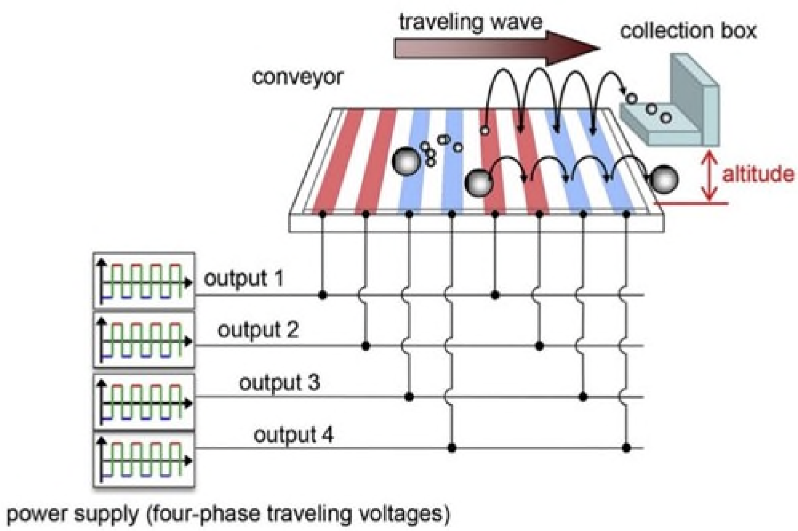

Figure 13. Experimental setup of the size-sorting system using an electrostatic traveling wave. The regolith particles can be transported, while smaller particles can be extracted by utilizing a force balance between electrostatic and gravitational forces [39].

Work Function Matching Coatings

The magnitude and direction of charge transfer between two materials when they are in contact is dependent on the difference between their work functions. As mentioned, the work function is the energy needed to remove an electron from the surface of a material, and it is relatively constant for metals, but not as consistent for insulators which do not have mobile surface electrons. When materials come into contact, charge is transferred such that their work functions are altered and come into equilibrium. This means that if two materials with the same work function come into contact with each other, there will be no charge transfer. Sternovsky, et al., conducted studies to estimate the work function of Lunar regolith simulant. It provided insight into which materials have a similar work function to that of Lunar regolith [42]. Of course, the closest match to the work function of Lunar regolith is the Lunar regolith itself. Therefore, the dust resistance effectiveness of a surface coating made from Lunar regolith simulant has been assessed and, as demonstrated in literature [43], such coating reduces the adhesion of Lunar simulants to thermal control surfaces. In the mentioned tests the coating was applied via ion beam sputter deposition using an argon ion beam source. This resulted in a 100nm thick coating.

Another method of coating materials with a Lunar regolith relies on using the Marangoni effect. This phenomenon is well understood but was first reported with Lunar regolith simulant by Dominguez and Whitlow [44]. They observed the upward migration of molten Lunar regolith in a crucible. The movement was driven by temperature gradients in the melt's bulk and along the crucible wall which created a surface tension strong enough to overcome the forces of gravity. The authors of this paper also observed the same phenomena while conducting experiments. A thin 0.5-mm Lunar regolith simulant coating was repeatedly produced by heating the simulant to its melting point under vacuum conditions. The coating's characteristics could be controlled by altering the amount of regolith used, the heating profile, and by doping the simulant. Three samples with varying coating heights can be seen in Figure 14.

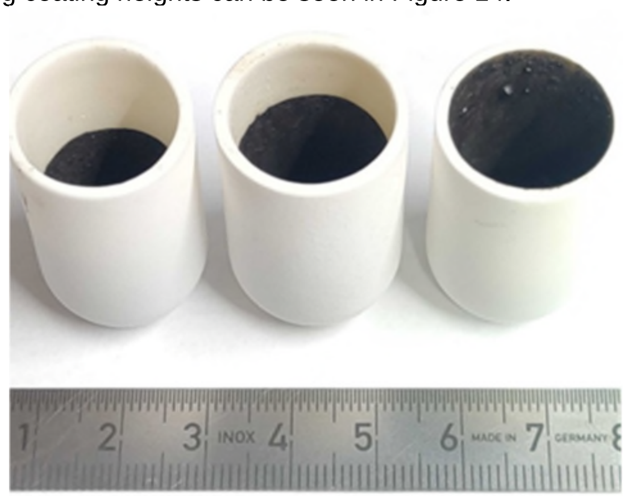

Figure 19. Marangoni effect coating with JSC-2A simulant.

This coating method is yet to be further tested for its dust mitigation effectiveness but based on the work of Gaier, et al. [43], it could lead to promising results. In addition, this process could lend itself to producing coatings for surfaces in-situ as the Lunar regolith is in abundance and the vacuum environment only needs heating to produce the ideal conditions. Furthermore, the process of coating could provide itself useful as a wear resistant coating against the abrasive Lunar dust. Again, this is yet to be tested but if the coating showed positive results, it would provide a double protection against both the Lunar dust adhesion and abrasion.

The method mentioned above aims at reducing the potential difference of hardware surfaces. But for extended contact with regolith another important factor is also the discharge mechanism. In a case where the charge on Lunar regolith is to be discharged, this is unlikely to work consistently if it is contacted against an insulating material or ungrounded conductor. This is because charge is conserved in triboelectric charge transfer. Negatively charged regolith in contact with neutral charging material of similar work function may lose some charge and the charging material will gain electrons. In this process the work function of the charging material will decrease, while the work function of the regolith will increase. In this case, the discharged regolith will begin to gain electrons back from the charging material, or any other regolith that encounters the charger will not discharge due to the saturation of electrons on the charging material.

To sustain discharging of Lunar regolith over long time periods, charge building up on the charging material gained from the regolith must be removed in order to make way for further charge. In an atmosphere it is possible to neutralize any material's charge using an ionizer. Using an ionizer is not possible in the Lunar vacuum however, since the working principle of an ionizer is to strip electrons from air molecules, yielding mobile charges that are attracted to and neutralize charged surfaces. The best way to ensure constant work function of a charging material is to use a conducting material and to ground it, keeping its electrostatic potential at zero. If a conducting material with similar work function to neutrally charged regolith is grounded, then any amount of charged regolith can be continuously contacted against the conductor and the regolith's charge will approach zero.

In addition to grounding a conducting material with a similar work function to Lunar regolith, it is possible to alter the work function of any conducting material in order to match it with that of the bulk regolith. This is done by applying a constant voltage to the conductor, raising, or lowering its Fermi level, and hence its work function. This can be tuned so that the charge on any contacting material (Lunar dust in this case) will gain net neutral charge when continuously charged against the biased conductor.

This work function altering process is displayed through the schematic in Figure 20. In Figure 20 a) an insulator and a grounded metal are shown, along with their work functions ϕ_I and ϕ_M respectively. These materials are contacted multiple times, leading to the transfer of electrons from the metal with a lower work function to the insulator, until their surface potentials come into equilibrium as shown in Figure 20 b). Figure 20 c) shows the case where a voltage V_{Apl} is applied to the metal, increasing its work function to ϕ_{Alt}. This in turn reduces the work function difference between the metal and the insulator, and hence reducing any charge transfer. If the polarity of V_{Apl} was switched, then the metal's work function would be decreased, and the insulator would gain extra charge compared to the grounded case.

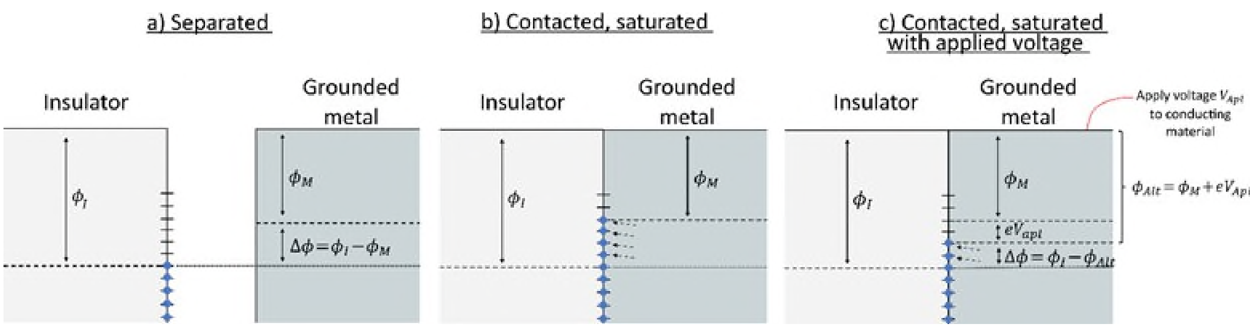

Figure 20: Schematic of the triboelectric charge transfer between an insulator and a metal based on their work functions when the metal is grounded (b) and when the metal has a voltage applied to it (c). The application of a voltage in order to alter the work function of a metal can be used in order to reduce the saturation charge of a contacting insulator.

This method of applying a voltage to a conductor charging an insulator has already been tested for triboelectric nanogenerator applications [45]. A parylene film was rubbed with a platinum coated tip, with applied voltages ranging from $-10\,V$ to $+\,10\,V$. They found that with an applied voltage of $\sim 3\,V$ the saturation charge of the parylene film was zero. For voltages $< 3\,V$ the film gained a negative charge, while at $> 3\,V$ the film gained positive charge. This proof of concept for neutralizing the charge on insulators contacting a conductor by applying a voltage is very promising, and points towards a potential method for the neutralization of charge on Lunar regolith.

Conclusions

Lunar dust has proven to be a challenging characteristic for surface missions. Since the Apollo missions, new technologies have been developped and some are ready to be further tested or even applied to flight hardware. We also demonstrated that the nature of the regolith adhesion is mainly electrostatic and therefore some traditional cleaning methods are not particularly useful. Nevertheless, in this paper, we presented different approaches to dust mitigation as well as examples of promising solutions. As shown, the available technolgies differ significantly and one should take them into careful consideration when designing Lunar hardware. Since there is no standard approach yet to the Lunar dust mitigation, the engineering community should be open to the implementation of novel solutions in future missions.

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