DEAR project: Lunar Dust Surface interactions, Risk and Removal investigations

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Abstract

The DEAR project (Dusty Environment Application Research) investigates the interaction between lunar regolith and surfaces and components relevant for lunar exploration. Based on the TUBS regolith simulant which is representative in chemistry, size and shape properties to Moon soils to study the regolith transport, adhesion and strategies for cleaning. The regolith simulant will be applied to thermal, structural, optical sensor, sealing and other astronautic systems, providing input for requirements, justification and verification.

The key applications are split in human space flight regolith investigations, wrinkled surface with random movement and hardware surfaces, flat material defined movement. The paper provides an overview of the DEAR project including a discussion of the first results, in particular vibration, shock and micro-vibration on regolith bearing surfaces. The investigation shall enable better understand the regolith layers interaction and the release mechanism, as well as potential cross contamination and cleaning strategies. The research is complemented by simulation of the regolith motion as parameter surface plasma interactions. The project is funded and supported by the European Space Agency (ESA). DEAR specifically addresses the development and testing of lunar dust removal strategies on optics, mechanisms and human space flight hardware (e.g., space suits). As the Moons regolith is known to be highly abrasive, electrically chargeable, and potentially chemically reactive, lunar dust might reduce the performance of hardware, such as cameras, thermal control surfaces and solar cells. The dust can cause malfunction on seals for on/off mechanisms or space suits. Of particular interest are risk assessment, avoidance, and cleaning techniques such as the use of electric fields to remove lunar dust from surfaces. Representative dust (e.g., regolith analogues of interesting landing sites) will be used in a dedicated test setup to evaluate risks and effects of lunar dust. We describe designs and methods developed by the DEAR consortium to deal with the regolith-related issues, in particular an electrode design to deflect regolith particles, cleaning of astronautical systems with CO2, design of a robotic arm for the testing within the DEAR chamber, regolith removal via shock, and regolith interaction with cleanroom textiles.

Keywords

Astronaut space suit, Electrode design, Regolith (lunar dust), Robot arm, Specific cleaning (CO2)

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1. Introduction

Interest in lunar exploration has regained thrust in recent years around the world. ESA, private industries, and the academic sector strive to explore the Earth’s satellite with ambitious new technologies. The hostile environment of the Moon, however, is generally perceived as a serious challenge, in particular the lunar dust. To minimise its impact on optical surfaces and mechanisms, seals, and in order to reduce operational risks during future lunar missions, the European Space Agency has contracted the DEAR (dusty environment application research) consortium to deal with regolith-related issues, catalysing European moon surface exploration missions in the near future.

1.1. Risks posed by Lunar Dust

Being highly abrasive, electrically chargeable, and potentially chemically reactive, lunar dust poses a high risk on the performance of hardware, such as cameras, thermal control, and solar cells. The dust can cause malfunctions on seals and influence the optical, mechanical and electrical as well as thermal properties of surfaces including space suits. For instance, during the sample processing on the lunar surface or in airlocks, reliable seals are mandatory. Furthermore, lunar dust is likely to be toxic and therefore needs to be avoided inside the lunar habitats, motivating the work on validated cleaning methods. Test setups shall be used to measure potential performance degradations within controlled dusty loads. A programmable robotic arm is used for repeated lifetime testing and for the mimic of the movement of an astronaut arm.

1.2. Cleaning methods

Cleaning is possible due to the avoidance of regolith dust built up or with active cleaning processes to remove the dust. Protection possibilities and cleaning efficiencies shall be experimentally extracted. In particular electrode structures creating electric AC fields for dust removal are in first order studied by simulation and test. Another cleaning method by applied vibration and shock is studied as well. The cleaning of astronautic systems is tested with CO_2 cleaning.

2. Discussion

2.1. Optical-Electrode simulation and Electrode breadboard

This work includes a simulation of how to remove dust particles covering optical windows e.g. photographic cameras, image sensors etc., utilising an electrostatic (electrophoretic) force on particles with inhomogeneous electric fields. The implementation of inhomogeneous electric fields is done via structured thin film electrodes, either metal films or transparent indium tin oxide (ITO) on a glass substrate. For simulation of the behaviour regarding the electrode, the following simulation codes are used:

- The Particle-in-Cell Monte-Carlo (PIC-MC) simulation code developed at IST Fraunhofer, using the distributed, parallel Poisson solver, which is based on the Gauss-Seidel algorithm with successive over relaxation (SOR).
- A simulation tool named “PALADIN”, for modelling the transport of macro-particles of variable sizes that considers particles of sizes ranging from nanometers up to millimeters, and may include various physical forces such as gravitation, gas friction, thermophoresis, charging and decharging, as well as electromagnetic field forces.

The combination of these tools allows the computation of the trajectories of a diluted ensemble of non-interacting nanoparticles on electrode structures. For a higher density of particles – as is the case of many dust layers covering a window, different simulation methods such as the Discrete Element Method (DEM) would be needed.

2.1.1. Simulation of electrode structure

Our simulation test geometry consists of a ceramic substrate material sized 10x10 mm^2 and a thickness of 1 mm (Fig.1). On the top side, the electrode structure is integrated into the substrate. It consists of metal lines with a thickness of 100 μm and a lateral width of 200 μm.

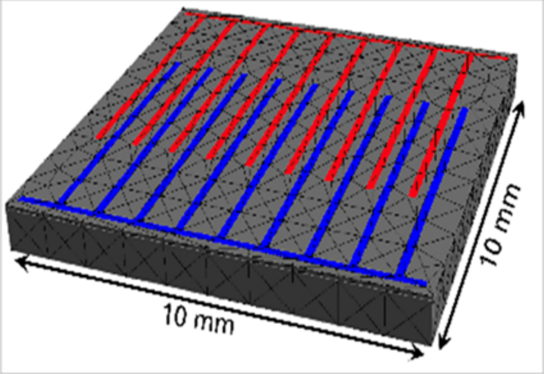

Figure 1. Geometric test structure used in simulation for various electrode designs

Two metal wire systems are connected to the positive and negative output of a voltage source.

Table 1. Basic parameters used for the electric field computation of the test structures

Parameter	**Value**	
	Low resolution	High resolution
Wafer thickness	1.0 mm	
Simulation box size	10 * 10 * 11 mm^3	
Segmentation	4 * 4 * 2 = 32 segments up to 32 CPUs	
Cell spacing	0.1 mm	0.05 mm
Number of cells	1.1 * 10^6	8.8 * 10^6
Electrode voltage	± 1000 V	
Substrate material	Ceramic material $\varepsilon_r = 6.0$	
Solver	Poisson equation; Distributed Gauss-Seidel with SOR	

The simulation volume for solving the electrostatic potential via the Poisson equation comprises the substrate plus a 10x10x10 mm^3 cube on top of the substrate, which is facing the side with the electrode structure.

The computed electric field, the resulting particle trajectories and the dielectrophoretic forces are shown in Fig. 2. For the PALADIN simulation, particles with a relative dielectric permittivity of $\varepsilon_r = 3.0$, mass density of $\rho = 3.5$ g/cm^3, and homogeneous size distribution between 10 - 500 µm are used.
Their starting positions are randomly distributed on the substrate surface with the electrode structure.
An important result is that on surface areas, where alternating poles are entangled, high electrophoretic forces up to several 100 g occur, allowing for particles to drift away from the electrodes. In contrast, in regions with only one polarity of the electrode structure, the dielectrophoretic forces are small, and particles have the tendency to remain sticking there.

2.2. Astronautic systems. Cleaning with CO$_2$

This activity is mainly focused on space suit materials but also equipment to be used by the astronauts. Following the “AMADEE-20” Mars analog field campaign in the Israeli Negev desert, a carefully selected crew of analog astronauts were deployed for one month.

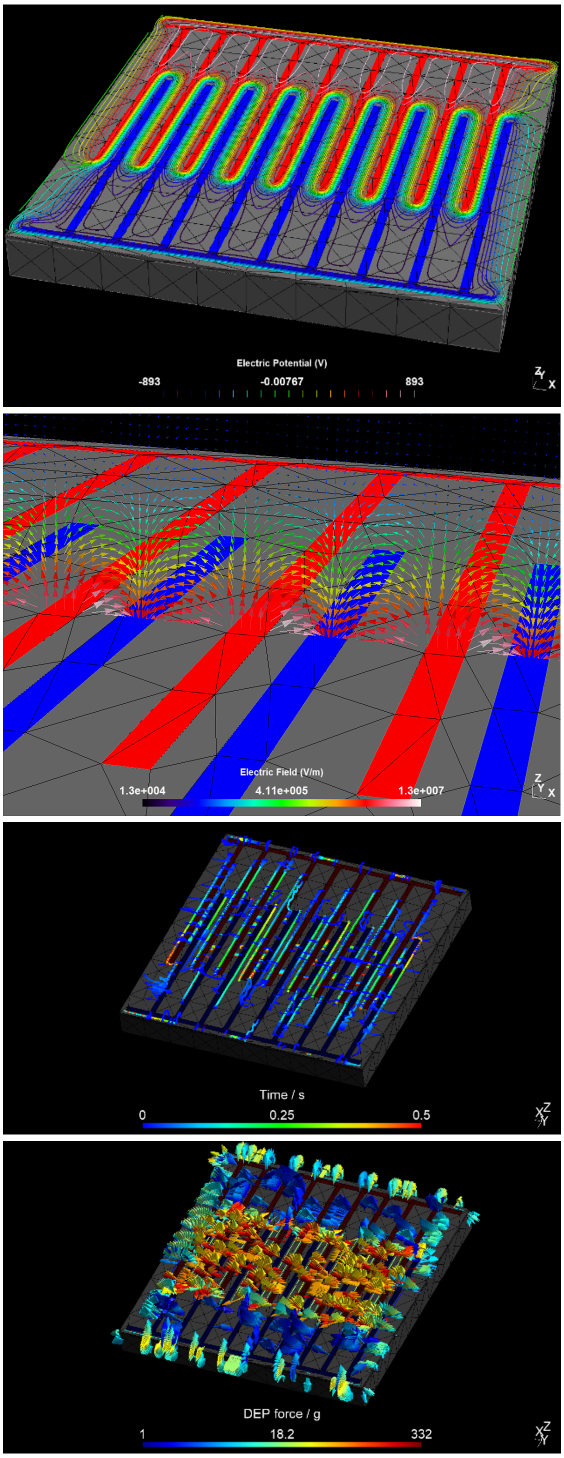

Figure 2. (1) Electric potential in a cut-plane located 100 µm above the substrate with the electrode structure;
(2) Central cut plane of the electric field showing the inhomogeneous regions in between alternating poles;
(3) Particle trajectories computed by PALADIN;
(4) Computed dielectrophoretic force in units of the gravitational field

Their work included performing simulated extra-vehicular activity (EVA) – with tasks pertinent also to lunar exploration, such as geosampling activities, maintaining critical hardware infrastructure of surface translation. In total, 61,35 EVA hours were conducted.

The spacesuits were representative of what is to be expected for future lunar missions, with a mass of 50 kg, 3 hour so donning time and a complex technical infrastructure for satisfying the needs of a human body, technical and biomedical monitoring and human metabolite management [2] and performing the EVA's in a manner pertinent to what is expected during a planetary surface operation [3].

Figure 3. Field work with spacesuit simulators during the AMADEE-20 expedition in Israel. (Photo courtesy of Florian Voggeneder (OeWF))

The surface textiles of the spacesuit simulators accumulated "regolith simulant" in a realistic fashion and were then transferred to a CO_2-cleaning facility to investigate the effectiveness of the cleaning workflow.

2.2.1. DEAR Test Textile Selection

The outermost layer to be focused upon will be in direct contact with regolith and the physical environment of the Moon. Based upon the parallel ESA project PExTex where dozens of candidate textiles were investigates, a shortlist of potential candidates was selected based upon the following criteria presented in Table 2:

The resistance to dust abrasion, electromagnetic compatibility (EMC) and discharge protection and dust mitigation were priorities for the choice. The selection is Inventex F1120Al, having following properties: (Kevlar ® orthofabric)

- Tensile strength 5 times higher than steel
- Permanently non-inflammable
- The fiber starts to degrade at 420 °C, for short duration can withstand higher temperatures
- Panox ® preoxygenated polyacrylnitril fiber with >60% carbon content very high LOI (limited oxygen index) of 45 starts to segregate graphite above 700°C and as such has a very high thermal resistance
- low mechanical strength → Kevlar has been combined

Table 2. Selection criteria

Withstand Lunar Temperature	Withstand and/or reduce Lunar radiation
Compatible with lunar vacuum	Must sustain pressure-vacuum cycling (?)
EMC and discharge protection	Resistance to wear by abrasive regolith
Bendability (?)	Fatigue integrity over the expected suit life
Shall not off-gas toxic substances	Shall be non-flammable
Dust mitigation	Impermeability to water and fluids

Several CO2 Cleaning Methods to remove lunar dust from the space suits are being tested, including blast cleaning with super-critical CO2 jets.

2.2.2.Benefits of Cleaning with CO_2

The CO_2 Snow-Jet Cleaning method requires 80% less space than conventional power-wash systems which are water-based. The time which is needed for one cleaning cycle is as well 80% shorter and the costs are reduced by up to 40%. This cleaning method is not adding any excess CO2 impact on the environment because the used CO2 has been re-captured from existing industrial emissions.

2.3. Robotic Arm

The objective is to develop a robotic arm testbed for the DEAR chamber. The testbed will be able to articulate in an easily programmable and repeatable manner with/without the application of lunar regolith, based upon a PincherX 150 robotic arm from Interbotix. The PincherX 150 Robot Arm features, 5 degrees of freedom using DYNAMIXEL XL430-W250-T smart servos motors, with a resolution of 4096 positions per rotation and user definable PID parameters. It allows the following parameters to be logged

- Cartesian Coordinate at end effecter (m)
- Angular Displacement of the joints (rad)
- Angular Velocity of the joints (rad/s)
- Effort produced by joints (Nm)
- Temperature of joints (°C)
- Present load of the joints (% of maximum torque)
- Input Voltage of each joint (V)

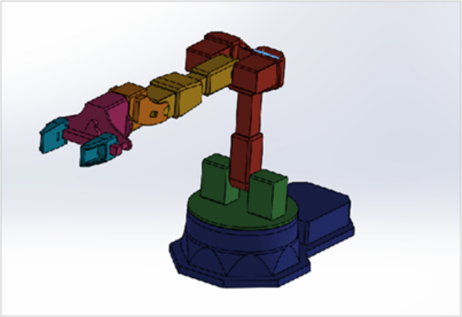

Figure 4. CAD drawing of PincherX-150 robot arm from Interbotix

The PincherX 150 is controlled by a Robotis DYNAMIXEL U2D2 which interfaces with a range of commonly available robotics software such as ROS, Gazebo, Coppella Sim and Move it.

It is of interest to measure the maximum payload the arms can reliably perform typical manoeuvers with. The Pincher- X150 is rated for a 50g payload at its end effector but can carry larger masses when the weight is distributed over the full length of the arm, as it the case when covered in textile. A series of tests were performed by wrapping the arm in a textile of known mass and measuring the maximum effort in the joints, during an "arm curl" movement repeated 50 time.

2.4. Regolith removal from surfaces using various external forces (shock, vibration, magnetic field)

One of the first choices to remove unwanted dust is a shock or vibration mechanism. Apart from the efficiency of the method, we bear in mind, an example of spatial activities with mechanical shock tasks as, for instance, the crushing station, part of the ExoMars rover, is equipped with a little hammer mechanism. After a drill sample is crushed, the hammer is applied to remove potential powder contamination from the sensitive surfaces prior to the next sample investigation.

2.4.1. Shock testing

Measure the displacement of dust applied to a surface by means of mechanical shock. The purpose of the experiment is to quantify the displacement of dust particles as function of the momentum transferred to the system. The control parameter is mass displacement for a well-defined mass, angle, and height of the pendulum (linear momentum transfer).

Experimental set-up consists of a pendulum with a rigid arm, a support, a Si wafer with applied regolith on it. The camera was used for recording of experiment. In a rectangular area of 50 x 16 (= 800 mm^2), we are placing the five types of particles, that differ by shape and sizes. The chosen particles for the experiment are: NaCl, anhydrous $CaSO_4$, $CaSO_4 * 2H_2O$, Talcum powder, regolith simulant TUBS-M.

Figure 5. Experimental setup

The set-up has been improved in the following way:

- The arm of pendulum is rigid and without torsion
- The area of particle covering is well defined by using a "window" of sieving the powder;
- The applied concussive force is automatic, excluding direct human intervention.

As control parameter, the mass of particles is measured, that has crossed the line on the side of the pendulum, by carefully removing the particles with fine brush into a watch glass, then measuring its weight. The control of the accuracy of that operation is done by weighting the remaining powder inside the initial area and deciding whether the difference to the original amount is within the limits of error tolerance. Experimental results are presented in Table 3.

Table 3. Experimental results for dust removal with identical shocks, and distribution of dust on surface

Particles type /% of displaced powder	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5
NaCl	19.34	31.53	39.74	32.98	36.06
$CaSO_4$ anh	24.65	20.91	40.86	27.45	66.60
$CaSO_4 * 2H_2O$	29.68	37.75	28.07	29.91	38.86
Talc	29.61	38.86	20.06	26.13	25.9
Regolith	66.5	57.5	46.66	50.88	50.80

2.5. Regolith interaction with textile

Motivation for this experiment is checking the border conditions (high and low pressure) and see how well cleanroom textiles can protect against fine Regolith particles.

2.5.1. Regolith penetration through textile by applying only gravitational force

Cleanroom textiles used in this experiment were by Dastex: ION-NOSTAT VI.2 without Carbon, and PFG DASTAT I1800. Using elastic bands, the textiles were tautly fixed on the beakers. A certain amount of Regolith was placed on the surface of textiles using a sieve. Then the beakers were sealed for 7 days in a chamber to exclude external disturbances such as streaming air. After 7 days, the chamber was unsealed and the beakers were taken out of it. The regolith on the top of textile surface was carefully removed, avoiding particle shoehorning. After that, the textiles were taken for an analysis. Observed range of lengths of particles that penetrated the textiles: ION-NOSTAT VI.2 without Carbon: 6,09 - 51,72 µm; PFG DASTAT I1800: 11,06 - 49,09 µm.

Experimental results are presented in Table 4.

Table 4 Experimental Data for Regolith penetration through textile by applying only gravitational force

Textile	Mass of Regolith before experiment (mg)	Mass of remained Regolith (mg)	Mass of Regolith penetrating the textile (mg)
ION – NOSTAT without Carbon	307,6	286,1	21,5
PFG DASTAT I1800	299,8	270,5	29,3

2.5.2. Regolith penetration thorough textile by applying additional pressure

Textile has been placed in a mortar, covering all mortar's surface. Regolith was placed on the surface of the textile, and then using a pestle it was forcefully pressed into the textile.

We have pressed 800 mg of Regolith against 26,5 cm^2 of both materials. The penetration rate, visually detected is in-between 5-10%. For calculation we have considered roughly 53 mg. The surface density of penetrated Regolith through textile (the control parameter) is then $53mg/26{,}5cm^2$, resulting $2mg/cm^2$, or 0,02 kg/m^2.

3. Conclusions

The DEAR project has been successful in achieving its objectives. Simulations of electrode structure suggests that on surface areas where alternating poles are entangled electrophoretic forces are pointing outward i.e., regolith will be removed outside of the covered area. Next steps will be the manufacture of prototypes to evaluate the results of simulation, investigation of effects from magnetic fields and adding the interaction between particles in simulations. Cleaning with CO_2 is also of particular interest because it can be used on a variety of human space flight hardware. Further investigations will be related to cleaning with CO_2 of robotic arm for wear issues and dust penetration. Robotic arm is an asset for doing experiments in regolith environments e.g., testing potential degradation of space suits exposed to regolith and testing mechanical systems in dusty environments. Regolith removal using mechanical shock is one of the simplest and effective methods, but further research is required.

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