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DUST mitigation technology for lunar exploration and colonization: existing and future perspectives

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Abstract. Micrometric dust particles of lunar regolith represent one of the most serious issues of the harsh moon environment. Indeed, the extremely high vacuum conditions expose the lunar soil minerals to intense ultraviolet and galactic cosmic rays' bombardment during the Moon's daylight producing photoionization of the constituent's atoms and electron release. Moreover, Moon periodically interacts with the surrounding solar wind which generates a continuous flux of charged particles is generated accompanied by electric fields around the terminator region able to lift off the lunar regolith dust up to ~100 km above the geometrical surface. In this way, micrometric granular matter forms a subtle veil of contaminants. This electrically charged and extremely adhering dust environment can cause various critical drawbacks not only to several robotic parts e.g., mechanical components, electronic devices, solar panels, thermal radiators, rovers seals and bearings, etc. but also can dramatically damage the respiratory systems of humans if accidentally inhaled. For these reasons, lunar dust was recognised, by several agencies including NASA and ESA, as one of the main potential showstoppers for the ongoing robotic and manned exploration and colonization of our natural satellite. For overcoming or at least mitigating these issues, several technologies were developed and assessed ranging from the active ones requiring a source of energy e.g., mechanical, fluidal and, above all, electric devices, to the passive technologies involving suitable material design and development. In the work here reported, the design and development of innovative high-performance polymers simultaneously exhibiting outstanding thermo-mechanical properties and superior non-sticking capacity i.e., *abhesion* to be applied for structural purposes on the Moon is presented. Further improvement of these suitable designed materials with the addition of appropriate electric properties will make them ideal candidates as dielectric substrates of a combined passive and electroactive system able to repel micrometric regolith particles i.e., lunar dust shield.

Introduction

Dust in space environments, especially Moon and Mars has been recognized by several Space Agencies, including NASA and ESA, as a major concern for the successful robotic and manned exploration and colonization of extra-terrestrial bodies.

Indeed, the Lunar surface is covered by regolith i.e., a loose granular material, consisting of a broad range of shapes, sizes, and types of sediments [1]. It mainly consists of silicate minerals e.g., olivine, pyroxene, plagioclase, and non-silicate minerals such as ilmenite [2], crushed by meteoric bombardment causing the fracturing, scattering and agglutination of lunar regolith in the form of micrometric (approximately 50% of the lunar regolith consists of granular, dust particle with diameters less than 60 μm [3]), sharp, abrasive, porous, chemically reactive dust particles. These granulometric particles are electrostatically charged by the interactions with the local plasma environment and the solar ultraviolet (UV) radiations as well as the solar wind due to the photoelectric effect i.e., the UV and X-ray induced photoemission of electrons of the grain-materials [4],5]. Even without any mechanical activities, the dust grains are levitated by the

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electrostatic fields and transported away from the surface in the near vacuum environment of the Moon. Above all, the lunar, regolith dust particles can adhere strongly to the exposed surfaces.

As verified during the Apollo missions, these particles were an unforeseen problem and caused several issues [6] including vision obscuration during landing [7]], abrasion of visors, gloves and boots of astronaut's suits [9], degradation of radiators and thermal control surfaces, deterioration of solar panels efficiency, deposition on optical surfaces, vision obscuration, creation of wrong responses from measuring devices and false instrument reading, interference with the operation of Extra-Vehicular Activity (EVA) systems including suits, airlocks, suitports tools, etc. [8].

In order to efficiently overcome the serious issues represented by the challenging lunar and Martian dust environments (or small bodies like asteroids, comets, and Near-Earth Objects), innovative technologies/approaches have to be investigated and employed.

They can be generally subdivided into passive and active approaches:

- **Passive dust mitigation technologies:** they consist in preventing the sticking and adherence of the loose granular fraction of lunar or Martian regolith i.e., micrometric dust (on the Moon the term dust usually refers to particles with a Sauter mean diameter < 25 μm). This ambitious and challenging goal is achieved without the application of any kind of external source of energy, by means of suitable design and development of special materials with the lowest possible surface energy, thanks to a tailored modification of the chemical structure further improved by a suitable alteration of the topographical/morphological features of the material's external layers due to application of several possible chemical and physical strategies.
- **Active dust mitigation technologies**: they foresee the direct cleaning of the examined surfaces or the protection of them from dust deposition and contamination. Active technologies utilize external forces: electrodynamic, electrostatic, fluidal, mechanical, etc. But the most effective ones are based on regolith particle charge. In detail, solar radiation and the solar wind produce a "plasma scabbard" near the lunar surface and lunar grains acquire charge in this environment and can exhibit unusual behaviour, including levitation and transport across the surface because of electric fields in the "plasma scabbard".

Results and Discussion

In order to solve or mitigate the dust issue, CIRA aims to pursue a hybrid strategy consisting of the simultaneous application of passive and active methods as depicted in Figure 1.

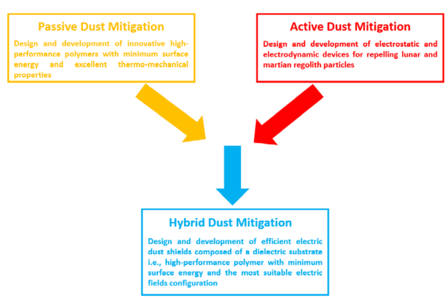

Figure 1. Scheme of the CIRA dust mitigation approach.

In particular, it can be accomplished by the design and development of a suitable material exhibiting at the same time minimum surface energy, i.e., *abhesion* capacity consisting of non-sticking ability against micrometric lunar dust particles, and excellent dielectric properties making it a good candidate as an insulating substrate of electrodynamic or electrostatic dust mitigation devices.

The harsh Moon environment requires also the design and development of a material endowed with outstanding thermo-mechanical properties in order to resist the strong temperature fluctuations, UV and galactic cosmic rays' irradiation, micro-meteoritic bombardment and ultra-vacuum conditions. Moreover, low density is another appealing characteristic for every material, which has to be transported from Earth and fly as payload within a space launcher. Considering also these constraints, the class of high-performance polymers has been recognized to be the most appropriate for lunar applications. In particular, aromatic polyimides (PI) have been selected as starting materials for achieving hybrid dust mitigation capacity.

According to this approach, CIRA has designed innovative aromatic PIs consisting of monomers endowed with a greater amount of trifluoromethyl groups in order to successfully employ the dipole-dipole repulsion forces exerted by the C-F groups, due to the highest electronegativity of the fluorine atom among all the elements. Furthermore, monomers containing a limited number of benzene rings have been identified since they guarantee the achievement of superior thermo-mechanical properties. Moreover, specially designed additives, Surface Migrating Agents (SMA) based on silicon moieties, have been formulated and they are able to spontaneously migrate toward the outermost layers of the material drawn by thermodynamic forces and react with the dianhydrides, used for the PI synthesis, forming a co-polyimide as shown in Figure 2.

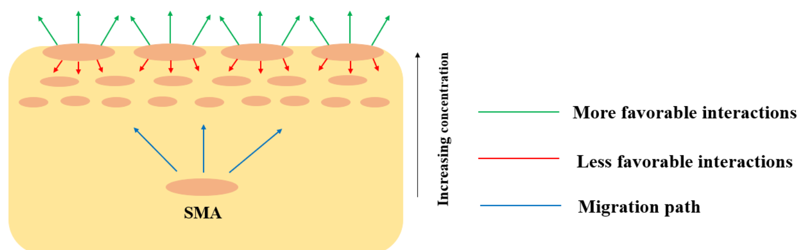

Figure 2. Schematic representation of the SMA migration mechanism.

The SMAs, reaching the external layers of the material, contribute to further lowering the surface energy, already minimized by the presence of elevated -CF_3 groups. This behaviour has been experimentally observed by the increase of the contact angles these coupons form with micrometric water droplets.

In order to realize a device endowed with passive and active dust mitigation capacity, this innovative PI has to be combined with a suitable electrodynamic system consisting of an array of thin conducting electrodes (Figure 3), embedded in the surface, and separated among them by an insulating material, designed to prevent electrical breakdown between the independent electrodes [7].

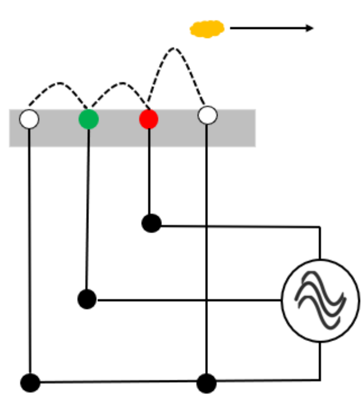

Figure 3: Schematic depicting dust particle motion on an electrodynamic system.

Electrodes are connected to a multi-phase low-frequency AC power supply, able to generate pulsed standing waves to shift, lift and transport far away charged particles, approaching the protected surface. Electrostatically charged particles, such as those encountered on the Moon, Mars, or on asteroids, are carried along by the traveling field due to the actions of Coulomb and dielectrophoretic forces.

Innovative materials developed by CIRA can be optimal candidates as insulating materials for electrodynamic devices for hybrid dust mitigation technology due to their inherent low dielectric strength.

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