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Proof of concept demonstration of novel technologies for lunar spacesuit dust mitigation

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ABSTRACT

A recent report by NASA identified dust/particulate mitigation techniques as a highly relevant study for future long-term planetary exploration missions (NASA, 2015). The deleterious effects of lunar dust on spacesuits discovered during the Apollo missions has compelled NASA to identify dust mitigation as a critical path for potential future lunar, asteroid and Mars missions. The complexity of spacesuit design has however constrained integrating existing dust cleaning technologies, formerly demonstrated on rigid surfaces, into the spacesuit system. Accordingly, this research is investigating novel methods to integrate dust mitigation technologies for use on spacesuits. We examine utilizing a novel combination of active and passive technologies integrated into the spacesuit outerlayer to alleviate dust contamination. Leveraging two specific technologies, the Electrodynamics Dust Shield (EDS) active technology and Work Function Matching Coating (WFM) passive technology, developed by NASA for rigid surfaces, we apply new high performance materials such as the Carbon Nanotube (CNT) flexible fibers to develop a spacesuit-integrated dust cleaning system. Through experiments conducted using JSC-1A lunar dust simulant on coupons made of spacesuit outerlayer material, feasibility of integrating the proposed dust cleaning system and its performance were assessed. Results from these preliminary experiments show that the integrated dust cleaning system is capable of removing 80–95% of dust from the spacesuit material demonstrating proof of concept. This paper describes the techniques and results from the experiments. Future challenges of implementing the proposed approach into fight suits are identified.

1. Introduction

Lunar dust proved to be problematic during Apollo missions degrading spacesuits and equipment, impacting operations, and posing health hazards when dust was brought into the lunar module. Voice transcripts of astronauts during the mission and post flight investigations of the Apollo suits (see Fig. 1) revealed the damaging effects of lunar dust on spacesuit components [2–4]. The lunar surface is characterized by several layers of thick regolith formed by high-velocity micrometeoroid impacts, and bombardment of charged atomic particles from sun and the stars. Lunar dust makes up the highly pulverized small particle portion of the regolith layer. Due to the lack of atmospheric weathering on the lunar surface these dust particles have sharp and jagged edges [5,6]. The dust particles are highly charged and the dry environmental conditions are conducive for these particles to hold the static charge developed and tend to adhere to surfaces readily coating them. Thus, the particles can become hazardous to spacesuits, surface operations, create communication failures, result in discharge breakdown, and cause other electronic equipment failures. In a recent Asteroid Redirect Mission report, NASA has identified dust/particulate mitigation as a high benefit, high relevance research area, and a critical path for potential future planetary missions [1].

While the Apollo program utilized basic methods such as manual brushing to remove dust from spacesuits and other equipment, it proved to be ineffective causing further abrasion of the spacesuit outerlayer [2]. Based on lessons learnt during the Apollo missions, several state of the art active and passive technologies have been proposed in literature for dust mitigation in the recent years. Most of these techniques are demonstrated

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Acronyms/Abbreviations

AC	Alternating Current
CNT	Carbon Nanotube
EMU	Extra-Vehicular Mobility Unit
EVA	Extra Vehicular Activity
EDS	Electrodynamic Dust Shield
GRC	Glenn Research Center
KSC	Kennedy Space Center
RH	Relative Humidity
WFM	Work Function Matching Coating
VAC	Volts of Alternating Current

for use on rigid surfaces such as solar panels, optical planes, glass structures and thermal radiators [7–12]. Application of these technologies for spacesuits however has remained a challenge due to the complexity of the suit design. Elements such as flexible structure of the soft areas of the suit, irregular contours and Teflon coated suit materials challenge the integration of these technologies into spacesuits.

This research is investigating novel techniques to develop a spacesuit-integrated dust cleaning system utilizing a combination of active and passive technologies. The study specifically addresses the technical and fabrication challenges of implementing WFM Coating passive technique, combined with EDS active electrode technology into spacesuits, by using yarns made of Carbon Nanotube (CNT) flexible fibers as electrode wires. The dust cleaning system proposed consists of embedded CNT fiber electrodes activated utilizing a multi-phase AC voltage signal which levitate and push the dust off the surface. The system is further augmented with WFM Coating made of lunar dust (in this case lunar simulant) that works to lower the adhesion of dust to the surface, thereby preventing further accumulation of dust. The combination of the CNT electrode EDS system along with the WFM Coating is proposed to provide an enhanced dust cleaning system for use in spacesuits for lunar missions. This technology can be extended to be compatible for Mars and asteroid missions as well.

A preliminary proof-of-concept study has been undertaken to determine the feasibility of the new materials and fabrication techniques for dust mitigation through experiments conducted on coupons made of spacesuit outerlayer 'orthofabric' material in ambient conditions using JSC-1A lunar dust simulant. The main objectives of these experiments are to explore the feasibility of the concepts, provide preliminary evaluation, and understand the challenges involved in utilizing these techniques for flight suit implementation.

Fig. 1. Apollo 12, Lunar Module pilot, Alan Bean's Suit coated in lunar dust [4].

2. Overview of Technologies Tested

2.1. Work function matching coatings

Passive dust mitigation technologies involve modifying the chemistry and/or the texture of the external surface exposed to dust in order to reduce dust adhesion. The coatings work to either control charge transfer in an effort to minimize the electrostatic forces, and/or to minimize surface energy, to decrease the adhesion between the surface and the dust. The WFM Coating works by altering the chemistry of the dust exposed surface and is particularly designed to minimize electrostatic forces of adhesion. Among the multiple charging mechanisms at work in the lunar environment, electrostatic forces and triboelectric-charging have been shown to be important and dominating mechanisms in cohesion and adhesion of lunar dust particles [12]. In theory, Work Function is the energy required to ionize (or remove) an electron from a material to a point outside the material. During triboelectric-charging, electrons are transferred from a material that easily loses electrons (i.e., has a low work function) to a material that holds tightly onto its electron (i.e., has a high work function) shown in Fig. 2 [13] causing the two materials to adhere. Triboelectric-charging can be minimized if the work function of the two surfaces coming into contact with each other are similar.

The underlying concept of the WFM Coating being assessed in this study has been previously developed and demonstrated by NASA Glenn Research Center (GRC) using the NU-LHT-1D highland lunar simulant [13]. Experiments conducted by Gaier et al. [13] on fluorinated ethylene propylene (FEP) and other thermal control surfaces in vacuum and dry conditions showed that modifying the surface chemistry of these dust exposed surfaces by applying ~100 nm thick WFM Coating showed promising results in the reduction of dust adhesion. In the context of the current research, matching the work function of the outerlayer of spacesuits to that of the lunar dust (dust simulant for earth based experiments) is proposed to minimize triboelectric charging, thereby reducing dust adhesion and further dust accumulation. Since the effectiveness of WFM Coating is prominent in vacuum and dry conditions as shown in previous studies, the scope for the current preliminary proof-of-concept study conducted in ambient conditions is limited to evaluating the feasibility of applying WFM over CNT fiber embedded orthofabric coupons. Furthermore, we estimated results from the experiments to understand if WFM Coating had any effect on the EDS performance.

2.2. Electrodynamic Dust Shield

EDS is an active technology developed by NASA that uses electrostatic and dielectrophoretic forces to carry dust particles off surfaces by generating a travelling electric field. The shield contains a series of parallel electrodes through which an Alternating Current (AC) of voltage is applied that generates a travelling wave of electric field as shown in Fig. 3 [7]. This electric field levitates and repels dust particles that travel along or against the direction of the wave, depending on their polarity, and prevents further accumulation of dust when kept activated. The electrodes can be excited by using a single or multi-phase AC voltage to remove charged and uncharged dust particles on the surface. First introduced by NASA in the 1960s as the Electric Curtain concept, this EDS technology was further developed for dust removal on rigid surfaces at NASA Kennedy Space Center (KSC) and other research groups []. Specific details on EDS are described in previous studies [7].

Several experiments previously conducted at NASA KSC demonstrate the feasibility and high efficiency of the EDS system for surface cleaning of solar panels, optical systems, glass structures and thermal radiators [7,11]. For example, in one of the experiments it was shown that when dust loading conditions using lunar dust simulant caused solar cell performance to drop to 11–23% of the baseline performance, activating transparent EDS restored solar cell performance values to above 90% [7].

Despite proof that EDS performs effectively as a dust mitigation strategy on rigid surfaces, implementing this technology for use on