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Practical performance of an electrostatic cleaning system for removal of lunar dust from optical elements utilizing electrostatic traveling wave

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ABSTRACT

The removal of lunar dust deposited on solar panels, heat radiators, and optical elements (e.g., lens and mirrors) is one of the critical issues for a long-term lunar exploration. We have developed a cleaning system to remove the deposited lunar dust using an electrostatic traveling wave. When a four-phase rectangular voltage is applied to a transparent plate consisting of circular vortical ITO (indium tin oxide) electrodes printed on a glass substrate to move the electrostatic field toward the outer direction, the lunar dust on the plate is removed outwards following the movement of the electrostatic traveling wave. In this study, the effects of pressure and temperature that simulate the lunar environment were investigated, and it was demonstrated that high performance was maintained in a harsh lunar environment. It was confirmed that the low-frequency mechanical vibration generated by the movement of a rover improves the cleaning efficiency. The actual energy consumption of this system was evaluated, and it was demonstrated to be negligible with a simple high voltage source.

1. Introduction

Many space agencies and commercial companies worldwide are planning to conduct large-scale manned and unmanned lunar explorations. The United States announced that National Aeronautics and Space Administration (NASA) will lead the return of humans to the Moon for long-term exploration and utilization of lunar resources, followed by human missions to Mars and other destinations. The Chinese Lunar Exploration Program (CLEP) is an ongoing series of robotic Moon missions by the China National Space Administration (CNSA). This program incorporates lunar orbiters, landers, rovers, and sample return spacecrafts. The Indian Space Research Organization (ISRO) is preparing to land its first lunar rover. The Japan Aerospace Exploration Agency (JAXA) is planning to send a rover in collaboration with India. Google Lunar X Prize is promoting the lunar explorations by private companies, and Moon Express is aiming to ultimately mine the Moon for natural resources of economic value.

Although lunar surface explorations had already been successfully conducted by the Soviet Union (Luna program) between 1959 and 1976, the United States (Apollo program) between 1969 and 1972, and China (Chang'e program) in 2013, there are still many technical problems [1–3]. Mitigation of dust is one of the most serious problems, as stated by Eugene A. Cernan, who is the last astronaut to walk on the Moon [4]. The lunar surface is covered by a regolith layer, and approximately 20% of the volume of the regolith layer consists of small particles called lunar dust that are less than 20 μm in diameter [5]. Because of its small size and the low gravity environment on the Moon, lunar dust is easily lofted when any disturbance such as the jet injection [6] and activities of the rovers and/or astronauts occurs. The electrostatic field created by the nonuniform charging of dust, owing to the radiation of solar wind and cosmic rays on the sunlight side of the uneven Moon surface, is another reason of dust whirling [7–13].

There are three main concerns regarding the lofted lunar dust. The first is that lunar dust adheres to the spacesuits [14–18]. The adhered dust brought into the lunar module after moonwalks by astronauts makes breathing without a helmet difficult, and these dust particles present in the cabin atmosphere affect the astronauts' vision. Substantial amount of dust particles with physical size of less than 2.5 μm (PM2.5) may cause occasional respiratory problems to the astronauts [19]. The second problem is that the lofted dust adheres to the mechanical parts of the exploration equipment coming into contact with bearings, seals, and gears; such a situation can lead to a catastrophic damage [20–25]. The third problem is that the lofted dust covers solar panels, heat radiators, and optical elements (e.g., lenses and mirrors), degrading their performance.

To overcome the last problem, Calle et al. [26–28] developed an electrostatic cleaning system to remove lunar dust adhering to the surface of solar cells based on a novel concept first proposed by Masuda et al. [29] A three-phase high voltage was applied to the parallel ITO (Indium Tin Oxide) electrodes of a spiral configuration on a plastic

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substrate. The dust particles on the plate were removed to the outside of the plate by the electrostatic traveling wave formed on the plate. It was demonstrated that the transparent dust shields applied to the commercial solar panels operated successfully under high vacuum even under extreme dust loading conditions that caused the solar cell performance to drop to 11–23% of its baseline performance. After dust shield activation, the solar cell performance recovered to values above 90%. Kawamoto et al. [30] developed a similar system that uses a four-phase rectangular voltage [31,32]. In addition to the confirmation of the basic performance, they demonstrated that the cleaning performance was improved by the application of ultrasonic vibrations; although the small particles were apt to adhere to the surface such that the optical performance was reduced by a few percent; further reductions were not observed after repeated operations, and both positively and negatively charged dust particles could be cleaned without changing the configuration of the system. Further, they successfully demonstrated the electrostatic removal of the actual lunar dust brought back by the Apollo 11 lunar surface mission. Numerical calculations based on the discrete element method predicted that the cleaning performance of the system is expected to improve further in the low-gravity environment of the Moon. This system is simple, has no mechanical moving parts, and consumes less power; thus, it is expected to be a reliable and efficient technology to mitigate the soiling of optical equipment used for long-term lunar explorations.

However, further investigation is needed to apply this technology in a harsh lunar environment. The actual lunar system requirements include; (1) the system must be compatible in low (−170 °C) and high temperature (110 °C), (2) it must work against mechanical vibrations, (3) the power source must be compact and light weight, and (4) the actual power consumption, including the power consumed by the high voltage source, must be low. In this study, we have investigated these issues to develop a practical cleaning system.

2. System configuration

The cleaning system shown in Fig. 1 consists of a high voltage source used to generate a four-phase high rectangular voltage designated in the upper left side of Fig. 1 and a cleaner plate with parallel electrodes printed on a substrate.

2.1. Cleaner plate

We have developed a cleaner plate as shown in Fig. 2. That is, transparent ITO (indium tin oxide) electrodes (four parallel lines in a spiral configuration) are printed on borosilicate glass substrates (100 mm × 100 mm), the width and pitch of the electrodes are 0.3 mm and 0.6 mm, respectively, the surface of the plate is coated with insulative adhesive, and the glass plate is covered with a thin film of 0.1 mm thickness made of borosilicate glass. Although the cleaning plate is similar to that used in our previous study [30], it was improved with respect to the insulation strength. In the previous plate, four terminals were placed closely at one corner of the glass plate, and the insulation breakdown sometimes occurred between the adjacent terminals of the high voltage application; therefore, they are separated at four corners of the plate. Another improvement is the adhesive between the glass substrate and the cover glass. We have tested several types of adhesive insulators, such as epoxy resin, UV-curable resin, and optically clear adhesive (OCA) film, and it was found that the OCA film is the most compatible insulator at high temperature.

2.2. High voltage source

A four-phase rectangular voltage was generated by using a set of positive and negative amplifiers switched by photo-MOS relays (AQV258, Panasonic) that were controlled by a microprocessor (MPU, PIC16F1623/1938, Microchip) [33]. A block diagram of the high voltage source is shown in Fig. 3. We adopted the small and low-capacity amplifiers (HVBT-1P-5 and HVBT-1N-5, max. ± 1 kV, 0.5 mA, W12.7 mm × D12.7 mm × H12.7 mm, Matsusada Precision) to generate negative and positive high voltages.

Fig. 4 shows the photograph of the prototype high voltage source (L125 mm × W70 mm × H40 mm, 180 g) and cleaner plate (L100 mm × W100 mm × T1.1 mm, 30 g).

3. Effect of pressure

To investigate the effect of pressure, the cleaner plate, on which the lunar regolith simulant FJS-1 [34] (0.1 g) was uniformly deposited, was placed in a vacuum chamber evacuated by a rotary vacuum pump that

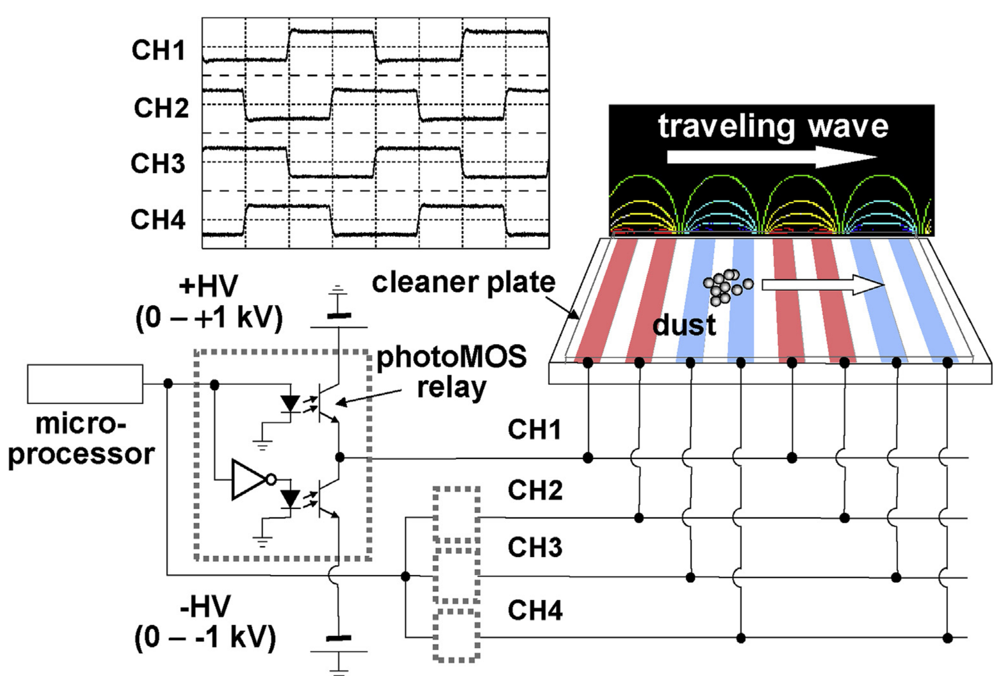

Fig. 1. Electrostatic cleaning system for removing lunar dust. (adopted from Ref. [30]).