Application of the particle trajectory imaging for modelling dusty plasma levitation on the Moon

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Abstract. The future robotic and human lunar landing missions to the Moon has many factors which turn them into difficult technology and science tasks. One of these factors is the influence of the dust. Upper layers of the regolith are an insulator. The regolith exposed to permanent bombardment by micrometeorites and acquire a charge due to solar wind fluxes and solar UV radiation. These factors create a charge distribution on the surface of the Moon: positive on the illuminated side and negative on the night side. On the day side of the Moon near the surface layer exists possibility of formation an electric field. Charged dust particles of micron and submicron sizes can take off and levitate over the surface. The aim of the work is to get visualization of the dynamic of dust particles under a charged surface with simultaneously estimating its parameters as accurately as possible. The experimental setup based on vacuum chamber for physical modelling of dusty plasma levitation is described. For visualization of the dust particles trajectory a stereo system of two cameras with a laser as source of illumination is used. Image processing techniques for estimating the particle trajectory in three dimensional coordinates and examples of processing results are presented.

1. Introduction

Recently, an interest in exploring the Moon has been reborn. Missions for this aim are declared by the USA, China, India, and the European Union. Russia also prepares two landing missions: Luna-Glob and Luna-Resource. But the future robotic and human lunar landing missions to the Moon have many factors which turn them into difficult technology and science tasks. One of these factors is the influence of lunar dust particles. Meteorites bombardment of the lunar surface, accompanied by shock-explosive phenomena causes disintegration and mix of the lunar soil in depth and on area simultaneously [1]. Under the influence of these factors, dust particles become one of the most active and aggressive components of lunar regolite, as well as regolith of any airless body of the solar system. Such particles, acquiring an electric charge under the influence of ultraviolet radiation from the Sun and solar wind, can rise above the surface of the Moon and levitate, creating a near-surface plasma-dust exosphere [2].

Properties of the regolith and the dust particles (density, temperature, composition, charge etc.) as well as near-surface lunar exosphere depend on solar activity, lunar local time and position of the Moon relative to the Earth’s magnetotail. Upper layers of the regolith are an insulator and it is charging by the solar UV radiation and the solar wind. These factors create a charge distribution on the surface of the Moon: positive on the illuminated side and negative on the night side [3]. Charge distribution depends on the local lunar time, latitude and the electrical properties of the regolith. On
the day side of the Moon near the surface layer exists possibility of formation an electric field. Dust particles of micron and submicron sizes are able to overcome the gravity force and the adhesive van der Waals forces in the electric field, take off and levitate above the surface [4]. An altitude of levitation depends on the near-surface electric field, charge and size of dust particles.

Important part of investigation of the lunar surface is study of dynamics dust particles under the regolith surface. Studying the properties of the lunar dust is important both for scientific purposes of lunar exosphere investigation [5] and for technical safety of robotic and manned missions [6]. PmL [7] a dust analysis device for future Russian flights is intended to study the dynamics of the dusty plasma near the lunar surface.

There are some recent articles [8-10] which present several approaches for modeling of the dusty plasma. Also, in some articles [8, 11] physical experimental modeling of this levitation is presented. The aim of our work is to get visualization of the dusty plasma with simultaneously estimating its parameters as accurately as possible.

2. Experimental setup

For conducting physical experiments on modelling the dusty plasma levitation an experimental setup was created (figure 1). It is based on a vacuum chamber. It consists of two parts. The first part is for creating conditions for the dusty particles levitation and it is including a system of supply and control of vacuum, a nonconductive substrate with dust particles on it, a steel grid above particles and a source of high voltage. High voltage from the source (2-12 kV) was applied to conductor on the bottom of the substrate. The particles of the dust with different materials and sizes were loaded on the substrate. The steel grid is located above the particles and connected to the ground of the high voltage source. Distance from the grid to substrate were changing in different experiments and was in range 3-8 mm.

The second part is optical visualization of the particles levitation. This part includes a vacuum viewport, a laser as a source of light, an optical system for illumination of an investigation the chamber volume, and a stereo system of CMOS cameras.

In the experimental setup a laser diode with wavelength 532 nm and power of 300 mW was used. The light from laser goes through the optical system of several lenses. The optical system expands the beam and makes its cross section close to rectangular. The expanded beam goes through the vacuum
viewport, reflects on mirror inside vacuum chamber on angle near 90° and illuminate the investigation area above the dusty particles. A volume of the investigation area was $5 \times 5 \times 3 \, \text{mm}^3$.

**Figure 2.** Direct visualization of the flight of SiO$_2$ particles with size of 40-100 μm (the thin lines on the picture).

Registration of images of the illuminated dusty particles was performed using the stereo system of two cameras. Baumer VLG-24M cameras with Sony IMX249 CMOS sensor, resolution 1920х1200 pixels and size of pixel $5.86 \times 5.86 \, \mu\text{m}^2$ were used.

**Figure 3.** The first stage of the stereo system images processing: (a), (b) – raw registered images; (c), (d) – images with noise reduction and thresholding.
3. Image processing technique

Image processing after the experiment is used to get complete information about particle trajectory. Trajectory should be reconstructed in three dimensional coordinates for estimating dust particles parameters as accurately as possible. A main problem of experimental images is lack of light in the investigation volume. Maximum power of the light source is limited by the possibility of an additional influence on the dust particles.

An image processing technique consists of several sequential operations. For each camera in the stereo system we:

- remove noise from images by subtracting each experimental image with a reference image without particles;
- binarize images with fixed threshold (figure 3 (c) and (d));
- detect connected components and filter them by their area and form.

Adaptive thresholding and Otsu method didn’t give appropriate results after processing due to high noise rate. So binarization with fixed and relative low threshold value (below 10-15) was used. Some images was filtered by performing morphology opening.

After these operations we process two corresponding images from the stereo system cameras:

- for each filtered connected component from the first camera we calculate the best match component on image from second camera by criteria of maximum normalized correlation coefficient (figure 4 (a) and (b));
- calculate two dimensional coordinates of corresponding points for two matched components (figure 4 (c) and (d));
- calculate three dimensional coordinates of the corresponding points (figure 5).

Last operation gives us 3d trajectory of particle. It can be fit to parabola for estimation of particle parameters.

![Figure 4](image)

**Figure 4.** The second stage of the stereo system images processing: (a), (b) – two matched contours on different images by criteria of maximum normalized correlation coefficient; (c), (d) – corresponding points for two matched contours.
For reconstruction three dimensional coordinates classic pinhole camera model was used. Before registration of experimental images cameras calibration with chessboard was done. Chessboard contains 8×7 squares with size of 5 mm. For each calibration 50 pairs of chessboard images in different positions were used. RMS error of calibration for single camera was below 0.5 pixel. RMS for stereo system calibration was in range 0.5-0.7 pixel.

Figure 5. Particle trajectory obtained after the image processing.

Figure 6. Particles' trajectories obtained after processing.
4. Conclusions
Visualization of the dusty plasma with simultaneously estimating its parameters is presented in this work. The experimental setup based on vacuum chamber for physical modelling of dusty plasma levitation is described. Visualization of the dust particles levitation is performed by the stereo system of two cameras. The particles were illuminated by a laser beam which is formed by special optic system.

Main aim of the work was determination of a trajectory of particle levitation in 3d coordinates. Trajectories was obtained by classical approach – calculating 3d point coordinates from 2d coordinates of points from different cameras of the stereo system. Maximum power of the light source was limited due to the possibility of an additional influence on the investigating particles. Therefore a lack of light in the investigation volume led to the need to use special image processing technique.

The proposed approach and image processing technique allow not only to visualize, but to obtain quantitative values of levitation parameters. These parameters make a valuable contribution to physical experiments on modelling the dusty plasma levitation and increase the likelihood of success of future robotic and human lunar landing missions to the Moon.

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