Reconstructing the Color 3D Tomography of Lunar Samples

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ABSTRACT: As the Chinese lunar exploration project prepares for future exploration activities on the Moon, there is a growing need to develop high-fidelity lunar soil simulants. The morphological analysis of lunar soil and its simulant is important for matching the unique properties of the agglutinates. To date, several techniques, including scanning electron, X-ray, and optical microscopies, have been extensively applied to analyze the three-dimensional (3D) morphology of lunar samples. However, none of these tools can acquire the natural color fine 3D microstructure of the samples, which is necessary to analyze components of the lunar meteorite and soil particles. In this letter, we present a high-resolution, natural color 3D tomographic system for the initial analysis of lunar samples. The superior performance of the system is demonstrated by the fine details and color 3D tomography of a lunar meteorite and lunar soil simulant. This method is expected to provide an essential tool for visually presenting the geological evolution of the Moon.

INTRODUCTION

At the end of 2020, Chang’E-5 has scooped a series of rare soil samples from the lunar regolith surface. These new samples provide vital data for the precise development of lunar soil models, evolution, calibrations, and verifications.1-4 In general, non-destructive measurements are first implemented for the analysis of lunar samples because of their ability to retain the original morphology and composition of the rare samples. Among them, optical testing is the key non-contact procedure that can quickly record vivid tomography and color information from a sample.5,6

Numerous monochromatic light micrographs of lunar soil particles can be found in existing literature.7 However, recovering the natural color and high-precision tomography of the entire sample remains a challenge for existing techniques. For instance, traditional macro-photography is limited by the depth-of-field of the objective lens, which leads to a blurred foreground and background in the obtained images. Thus, macro-photography is unsuitable for high-resolution three-dimensional (3D) surface reconstruction. In recent decades, various optical techniques have been developed to supplement the measurement of 3D surface morphology for millimeter-sized objects, including confocal laser scanning microscopy (CLSM), white-light interference microscopy, and structured illumination microscopy (SIM).8-10. These technologies have significantly improved our understanding of particle microstructures.

CLSM is presently the most widely used optical sectioning technique. It requires the scanning of the illumination spot, which remains in focus with the pinhole aperture. The out-of-focus background is filtered using a pinhole aperture.11 However, the laser power used for CLSM is approximately 10^6 W/cm^2, which may damage the lunar soil sample. Additionally, the point-by-point scanning method is slow and laborious. Scanning white-light interferometry (WLI) is a well-established method for determining object shapes with height variations from a few nanometers to several hundred micrometers.12 WLI measures the 3D surface profiles by scanning the sample and recording the white-light interference pattern generated by a specially designed objective. Unfortunately, the speckle patterns of different wavelengths...
become decorrelated at locations with high surface slopes. Consequently, white light interferometry is only effective for optically flat surfaces, and the angular soil reduces the measurement precision of the interferometry scans.13

SIM is another method used to perform optical sectioning. Optical sectioning SIM (OS-SIM) uses fringe illumination patterns to modulate the in-focus and out-of-focus information of specimens. The in-focus information can be calculated from the raw data owing to the sharp decrease in modulation with defocus14. OS-SIM has the highest imaging speed in the above-mentioned methods, and it ensures as good an axial resolution as CLSM. Thus, it is widely used in insectology, materialogy, and geology.15 Another advantage of OS-SIM is its ability to obtain the natural color of a sample. Many fine 3D structures of lunar soil have been imaged, but few high-magnification color micrographs have been published. This is primarily because the 3D surface morphology mentioned above cannot obtain the color information of the samples. The color of lunar soil is an important characteristic in many aspects because it reveals the chemical composition, layered structure, and maturity of the soil.16-18 In 2011, Kiely et al. proposed the imaging of individual particles using X-ray micrographs for submicron resolution and optical micrographs for color texture information.19 However, this method was unable to simultaneously collect color and fine structural details.

In this study, we demonstrate a high-dynamic-range color structured illumination microscope (HDR-C-SIM) for imaging 3D morphological data and natural colors of the specimens. The color 3D tomography results show the fine details of lunar soil simulants and a lunar meteorite. The design of the system is based on our previous C-SIM, in which colorful 3D images of insects and amber inclusions were captured.20, 21 The illumination power in our HDR-C-SIM is less than $10^{-14}$W/cm², which is 6–7 orders of magnitude lower than that of the CLSM, and it cannot damage the precious samples. Compared with other 3D surface morphologies, the HDR-C-SIM system provides high resolution, large scale, fast imaging speed, and, in particular, natural color. Our approach demonstrates the outstanding performance of the HDR-C-SIM in geological research, thereby providing a new and powerful tool for the study of soil and rock particles.

**METHODS**

**Sample description.** Two types of samples are prepared to demonstrate our system. We first image two simulated lunar soil particles, which are acquired from the Sihai volcanic cinder, Jilin Province, eastern China and prepared by the Chinese Academy of Sciences. Simulated lunar soil is a geochemical replica of lunar samples.22 Physical and chemical property analyses revealed that the CAS-1 simulated lunar soil samples are ideal low-titanium basalt simulated lunar soil, and share a similar chemical composition, mineral composition, and physical and mechanical features with the lunar samples collected by Apollo 14.23 Next, a millimeter-level lunar breccia is imaged, which is considerably larger and more colorful than the soil particles. It is one of many identical-appearing pieces from Northwest Africa (NWA) 11474, which primarily consists of feldspathic clasts and shock melt with lower amounts of fragmental pyroxene and olivine. A saw cut revealed fragmented breccia with numerous white feldspathic clasts set in a dark-gray ground mass.24, 25

**Principle of HDR-C-SIM.** Only a small part of the sample is in sharp focus in a single shot because the image is limited by the depth-of-field of the conventional wide-field microscope. The in-focus information is always merged with the blurred foreground and background, which severely degrades the imaging quality. Herein, we propose a one-dimensional sequence Hilbert transform (SHT) algorithm to decode in-focus and color information.26 In the HDR-C-SIM system, two sinusoidal fringes with a $\pi$ phase shift are projected onto the specimen, thereby forming the structured illumination. Using the properties of the Hilbert transform, we can demodulate the sinusoidal amplitude and obtain the in-focus information $I_{os}$ as follows:

$$I_{os} = \sqrt{(I_2 - I_1)^2 + (H(I_2 - I_1))^2}$$  \hspace{1cm} (1)

$I_1$, $I_2$, and $H$ denote the two raw structured images and the Hilbert transform, respectively. The proposed algorithm reconstructs the optical sectioned image using only two images, which reduces the acquisition time by 33% and permits a fast and phase-shift-free method to obtain the in-focus information compared with the traditional algorithm.26

To restore the color information of the samples, it is necessary to convert the raw data into the RGB space, calculate the SHT algorithm in three channels, and recombine the data. However, this method is time-consuming in processing the huge raw data, particularly for large and thick samples.15 Herein, we apply a simpler principle to decode the color information and increase the reconstruction speed as the flowchart shown in Fig. 1. For each layer, after the image is acquired by a color sCMOS camera, two raw images are added to produce a uniform wide-field image as follows:

$$I_{osf} (RGB) = \frac{I_1 (RGB) + I_2 (RGB)}{2}$$  \hspace{1cm} (2)

Next, we convert the raw images into grayscale and calculate the optical sectioned image using Eq. (1). Because the wide-field image carries all the color information of the sample, we can obtain the result by multiplying $I_{osf} (Gray)$ and $I_{osf} (RGB)$. Finally, a 3D color optical sectioned image of the sample is
obtained by axially scanning and superposing the reconstructed results of each layer. After reconstruct the height map by optical sectioned image, it is easy to calculate the volume as well as the surface area of the three samples. The volume equals the sum of the volume of each pixel which is calculated by multiplying the height and base area. The surface area is obtained by fitting the surface with small triangles in pixels and adding up the areas of all the triangles. As a result, the HDR-C-SIM enables a fast and efficient method to obtain optical sectioned images with natural color, particularly when imaging large and thick samples.

**Experimental Setup.** The HDR-C-SIM system which is designed to simultaneously capture 3D tomography and color, is illustrated in Fig. 2. The warm white illumination light emitted by a high-power LED (SOLIS 3C, Thorlabs Inc., USA) is reflected by a total-internal-reflection-prism (TIR-prism) and directed onto a DMD chip (V-7000, 1024×768, ViALUX GmbH, Germany). The modulated light field then passes through an achromatic collimating lens and a beam splitter, and is projected onto the focal plane of the objective lens. The sample is mounted onto a custom-designed sample holder, which is fixed on a xyz compact linear stage (3-M-122.2DD1, 25 mm travel range, Physik Instrumente GmbH & Co. KG, Germany). For each axial plane in the z-scanning, two fringe-illuminated raw images are captured with an adjacent phase shift of π. Volume data for the different axial layers are obtained by moving the specimen through different z positions to acquire 3D light intensity distribution data for the specimen.

**RESULTS**

Surface topography and natural color are important in the formation and evolution of lunar soil. However, there are few technologies that can simultaneously image fine details and color. Herein, we prepare two types of samples to demonstrate our system: a lunar meteorite from Africa and a lunar soil simulant.

We present the first report of the 3D color structure of two simulated lunar soil particles. Three-dimensional structural analysis based on the HDR-C-SIM revealed three views and a height heat map of two irregular CAS-1 simulated lunar soil particles. For the particle shown in Fig. 3a and Visualization S1, the entire 3D volume is 528 × 360 × 218 μm³, and is captured using a 20 × / NA 0.45 objective. The period of the sinusoidal fringes on the sample is 1.08 μm. The volume and surface area calculated using the height map are 1.454 × 10⁻² mm³ and 0.4238 mm², respectively. The total data acquisition time is 23 s, that is, 30 ms exposure time × 2 patterns × 328 layers + 10 ms Z-stage settling time × 327 axial slice intervals. There is no additional calculation time because the SHT algorithm requires less than 30 ms to calculate one optical sectioned color image. Thus, imaging and calculation are processed simultaneously in the self-developed controlling software. For the smaller particle shown in Fig. 3e and Visualization S2, we capture the images using a 40 × / NA 0.75 objective and the sinusoidal fringes on the sample have a period of 0.54 μm. The entire 3D volume is 370 × 279 × 40 μm³. The volume and surface area calculated using the height map are 1.342×10⁻³ mm³ and 0.1961 mm², respectively. The total data acquisition time is 22 s, that is, 50 ms exposure time × 2 patterns × 200 layers + 10 ms Z-stage settling time × 199 axial slice intervals. Furthermore, the natural color recognition shows that most regions of this particle are yellowish, white, and gray, which are important features of anorthose. This indicates that the particle primarily consists of anorthose. In addition, an HDR-C-SIM equipped with Raman spectroscopy may become a powerful tool for future in situ and non-destructive research of mineral structures and chemical compositions.
Fig. 3 Maximum intensity projection images of individual lunar regolith simulant particles. (a)-(c) The frontal view, right view, and bottom view maximum intensity projection images of the larger particle. (d) 3D morphological height map of (a) and the depth profiles along the solid line in the height map. (e)-(h) The similar view of the smaller particle results.

Taking advantage of the high imaging speed, we next report the 3D color structure of a millimeter-level sample from a fragment of Northwest Africa (NWA) 11474. The traditional way to study lunar meteorites is to use scanning electron microscopy (SEM) for imaging, which requires critical and contaminated sample preparation and a long imaging time. Using HDR-C-SIM, colorful fine structures can be easily acquired, as shown in Fig. 4 and Visualization S3. Because the entire volume of 11.1 × 8.1 × 4.4 mm³ is too large for microscopes, the result is stitched using 48 datasets (8 horizontal × 6 vertical). Each of the raw images is captured using a 4 × / NA0.2 objective, which leads to a 1.25 μm lateral resolution, and the scanning interval is 15 μm, which agrees with the axial resolution. The period of the sinusoidal fringes on the sample is 2.75 μm. The volume and surface area calculated using the height map are 145.8 mm³ and 572.5 mm², respectively. The total data acquisition time is 296 s, that is, (10 ms exposure time × 2 patterns × 293 layers + 10 ms Z-stage settling time × 292 axial slice intervals) × 48 fields-of-view. If a laser scanning imaging method, such as confocal microscopy, is used to collect the same amount of data, it may require hours of imaging time. Results show white clasts that are rich in feldspar and red patches that are known as caliche stains. These results are consistent with the nano-scale Fourier Transform infrared spectra collected by Caliskan et al.\(^27\)

**DISCUSSION AND CONCLUSION**

It is worth noting that the image color of the sample is also affected by illumination, which is primarily introduced by the correlated color temperature of the light source. The LED illuminant that we used (SOLIS-3C, Thorlabs, USA) is specially designed for
microscopy. Thus, it exports daylight white at a 5700 K correlated color temperature. However, this temperature is lower than that of the typical fluorescent lamp (~6000 K), and images captured by the camera are warm and reddened. To compensate the color error caused by the color temperature, the results should be manually post-processed. This operation requires expert knowledge and is repeated every time-step. Therefore, for imaging with the HDR-C-SIM and other colored microscopies, we recommend using white-balancing cameras. When the white balancing is carefully adjusted, the problem is mitigated at once, and it is possible to achieve results with true color, as shown in Fig. 4.

Raman spectroscopy is a valuable and widely used technique in the Earth and planetary sciences. There are alternative methods of exciting/probing the Raman effect, such as surface- and tip-enhanced Raman spectroscopy, coherent anti-Stokes Raman scattering, and time-resolved Raman spectroscopy, which are now slowly emerging in the Earth and planetary sciences. Matrajt et al. identified a highly disordered macromolecular carbonaceous component from the Tagish Lake meteorites using Raman micro-spectroscopy, which is verified to be aliphatic. However, Raman analysis is complex and time-consuming, and researchers can only test several random fragments. Thus, we suggest combining the two techniques in a hybrid arrangement, and we expect to obtain the sub-micron mineral structure, natural color, and chemical composition simultaneously. First, the precise optical sectioning can be imaged to identify the areas of interest using the HDR-C-SIM described in this study. Then, the chemical composition can

Fig. 4 Maximum intensity projection images of NWA 11474. (a)-(c) The frontal view, right view, and bottom view maximum intensity projection images of the meteorite obtained with the HDR-C-SIM system, respectively. (d) 3D morphological height map along the frontal view and the depth profiles along the solid line in the height map. (e)-(n) The close-up view and the depth profiles of the square ROIs in (a), respectively.
be analyzed using micro-Raman spectroscopy. In this way, we can realize the rapid identification and detection of samples.

In this study, we have demonstrated the utility of the HDR-C-SIM in geological research by investigating the 3D morphology and colors of two different samples, including lunar soil simulant and a lunar meteorite. Compared with other 3D surface morphologies for micrometer-sized and millimeter-sized objects, the HDR-C-SIM has the advantages of providing color, low thermal damage, and high imaging speed. We believe that the HDR-C-SIM will improve and provide further applications in geological research.

ASSOCIATED CONTENT
The supporting information (Visualization S1-S3) is available at www.at-spectrosc.com/as/home

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Notes
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