TEMMI: A Three Dimensional Exploration Multispectral Microscope Imager for Future Planetary Missions.
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Introduction: Past, current and future missions to the surface of Mars and the Moon include high-resolution microscopic imagers [1-5]. High-resolution three-dimensional (3D) microscopic images provide morphologic, structural, textural and in some cases chemical information that are of utmost importance for conducting field investigations of planetary surfaces. A geologist may utilize such data to interpret soils, rock type and possibly the formation and weathering histories from the morphology of microtextures and grain-size/properties. Such data may also be useful for detecting signs of past or present biological activity – as noted by Schopf and Kudryavtsev [6], accurate documentation of 3D morphology of microfossils is one of the most important outstanding "problems confronting the study of ancient permineralized (petrified) microscopic fossils". This may provide invaluable context and targeting information when accompanied by other precision-based instruments on exploration missions. Several missions have now included a microscopic imager as highlighted by NASA – Mission Highlights [3].

The proceeding sections introduce and summarize the capabilities of the Three Dimensional Exploration Multispectral Microscope (TEMMI). We also demonstrate TEMMI's imaging quality on geologic materials, specifically impactites from various terrestrial impact structures, which may be analogous to structures found on both the Lunar and Martian surfaces.

TEMMI Design: TEMMI was designed and developed for the Canadian Space Agency by two industrial partners, MacDonald, Dettwiler and Associated Ltd (MDA) and National Optics Institute (INO) along with three investigative academic partners, Western University Canada, The University of New Brunswick and York University [7]. An advanced prototype of TEMMI has been built and tested for rover-mounted operation in terrestrial analog field trials. TEMMI consists of a monochrome camera mounted to a microscope objective. Attached are three identical LED-based illumination units making TEMMI independent of natural lighting as well as a digital light processor (DLP)-based video projector with a white LED and an objective. Both objectives are custom designs employing a modified Offner reflective configuration, which makes them very robust to facilitate the development for flight readiness. An internal focusing stage is used to adjust the distance to the sample. In order to accommodate field trials and integration on different rover platforms, the TEMMI prototype is housed in a single enclosure incorporating optics and all control electronics and requires only data and power connections to operate. TEMMI is fully remote controlled and provides all software for control and data processing.

TEMMI Specifications: TEMMI offers three modes of operation. In the 2D color mode, images are acquired using illumination from eight different LED lights, covering the wavelength range of the visible and the near infrared (VNIR) from 455 nm to 850 nm. In this mode, calibrated reflectance images at the LED wavelengths, which can be combined into RGB color images, are obtained. In addition, diagnostic absorptions in the VNIR short of 1 μm are specifically sensitive to outer-shell electron transitions in transition metal cations, especially iron (Fe). As such, the TEMMI 8-point spectra may be used to discriminate ferrous (Fe^{2+})- and ferric (Fe^{3+}) iron-bearing minerals common to the Moon and Mars (e.g., Fig. 1). In the 3D mode, a number of images are taken using a DLP to project Moiré patterns from which a topographical map of the sample is calculated with lateral resolution of 5 μm and vertical resolution of 2 μm. 3D color composite images are derived by overlaying their corresponding 2D color image on their DLP - derived digital topography model. TEMMI also includes a fluorescence mode, for which a LED light at 365 nm may excite visible fluorescence in biomolecules or minerals that are specifically sensitive to ultraviolet wavelengths.

Two imaging modes are implemented for color and fluorescence imaging, the low-resolution mode providing a field of view (FOV) of 5.7 x 4.3 mm with optical resolution of ≤ 10 μm (4.4 μm pixel resolution) while the high-resolution mode provides a FOV of 5.7 x 2.1 mm with ≤ 5 μm optical resolution (2.2 μm pixel resolution). An internal focusing stage positions the microscope around the working distance of 25 mm (range +5/-20 mm). The native depth of field (DOF) is less than 20 μm but TEMMI implements focus stacking to provide extended DOF of up to several millimeters.

Demonstration: The purpose of the collaboration with the academic community is to demonstrate the application of TEMMI in the context of geologic materials and relevant geologic investigations. The images in Fig. 2 are taken in a laboratory environment in order to show TEMMI's images at their full potential. As TEMMI is designed to operate at these specifications on a rover, the images provided will ideally mimic those taken in a Martian or Lunar environment. From the images one can study the physical and structural properties of any sample, which may then be interpreted to give relevant geological and/or biological information.

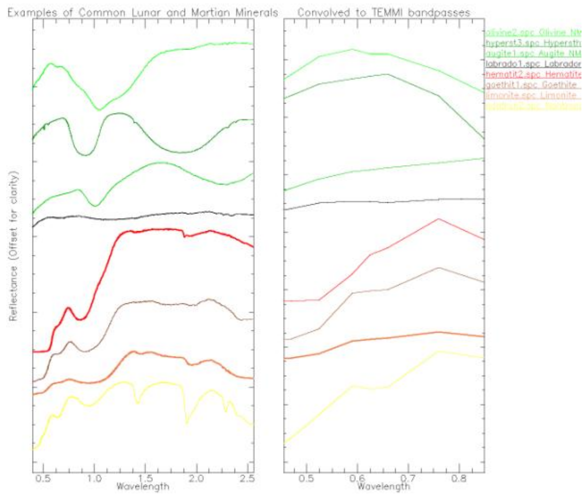

Figure 1. Left: selected minerals common to the Moon and/or Mars from the USGS VNIR spectral library. Right: the same minerals resampled to the eight TEMMI VNIR bandpasses [8].

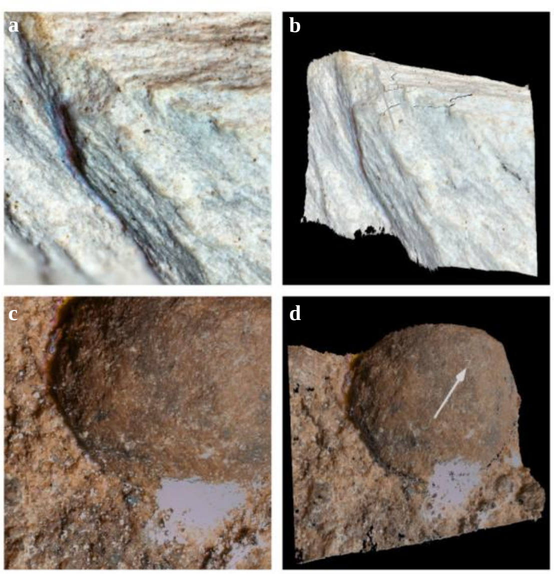

Figure 2. Left: low-resolution color images with a FOV of 5.7 x 4.3 mm, Right: 3D perspectives of the same images from (a) and (c) draped on their derived 3D models.

Figure 2 shows a set of images of impactites (a shatter cone and a melt-bearing rock) including low-resolution color images (Figs. 2a and c) and a screenshot of 3D color composite images (Figs. 2b and d). The micro morphologies become quite apparent in these samples by utilizing TEMMI's focus stacking capabilities along with the 3D mapping. Fig. 2a and Fig. 2b are TEMMI images of the surface of a shatter cone – the only macroscopic indicator of the high shock deformation for an impact event [9]. The characteristic conical and striated "horse-tail" structures captured by TEMMI are a diagnostic feature of shatter cones. The conical nature of the shatter cone, relevant to the proper identification of such a feature, is underappreciated in the 2D image, but is easily recognized in the 3D. Fig. 2c and Fig. 2d show a spherical, concretion-like feature in a melt-bearing rock that is reminiscent of the hematite-rich martian 'blueberries' that were discovered by the Opportunity Rover in Meridiani Planum on Mars [10]. Like the shatter cone, the spherical nature of the putative concretion is not clear in the 2D image, but is easily discerned in the 3D. The images taken by TEMMI in Fig. 2 may be analogous to features and structures that may be found in a Martian and/or Lunar environment. As such, the high-resolution, multiwavelength, and 3D capability of TEMMI may prove invaluable for determining the geologic histories of the materials investigated by future roving missions.

Future Work: Ruggedizing the mechanical design and advancing the electronic design towards flight are important steps towards a flight design. Also, image acquisition and processing are currently lengthy processes which could be improved by dedicated computing hardware. Further laboratory investigations, including the utilization of the 8-point spectral data to distinguish geologic materials at microscales, and trials of rover-mounted operations in terrestrial analog sites are forthcoming.

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