SURFACE, NAVIGATION AND PANORAMA 3D CAMERAS TAILORED FOR LUNAR AND MARS ROVERS: A CASE STUDY ON LUVMI-X. N. Murray[1], A. Evagora[1], S. Murray[1], T. Chupin[2], J. Gancet[2], D. Urbina[2], H-K. Madakashira[2], D. Fodorcan[2], G. Fau[2], R. Aked[2], S. Barber[3], S. Sheridan[3], J. Schwanethal[3], L. Richter[4], M. Reganaz[4], J. Biswas[5], C. Gscheidle[5], M. Losekamm[6], T. Poeschl[6], S. Schroeder[7], D. Vogt[7], J. Neumann[8] and P. Wessels[8]. [1]Dynamic Imaging Analytics, Milton Keynes, MK14 6GD, UK neil.murray@dynamicimaginganalytics.co.uk [2]Space Applications Services NV/SA, Leuvensesteenweg 325, 1932 Sint-Stevens-Woluwe, Belgium, [3]The Open University, MK7 6AA, Milton Keynes, UK, [4]OHB System AG, Manfred-Fuchs-Straße 1, 82234 Weßling, Germany, [5]Technical University of Munich, Institute of Astronautics, Boltzmannstraße 15, 85748 Garching, Germany, [6]Technical University of Munich, Department of Physics, James-Franck-Straße 1, 85748 Garching, Germany, [7]German Aerospace Center (DLR), Institut für Optische Sensorsysteme, Rutherfordstraße 2, 12489 Berlin-Adlershof, Germany, [8]Laser Zentrum Hannover e.V. Hollerithallee 8, 30419 Hannover, Germany

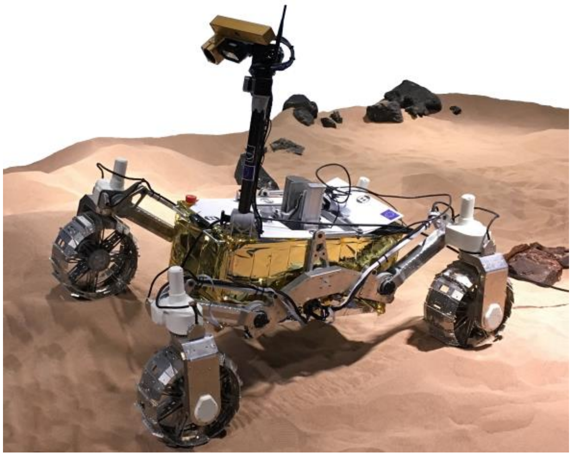

Figure 1: The LUVMI-X rover prototype during trials.

Introduction: A new generation of rovers is being developed to explore the Moon, motivated by the prospect of finding water ice that could advance scientific discovery and may provide a source of oxygen to support human and robotic exploration. These missions play by new rules, with commercial entities working in partnerships with traditional space agencies to develop rovers that are smaller and faster to develop, yet highly capable and innovative. And in turn a new approach to exploration platforms inspires and requires a new approach to developing high performance instrumentation on rapid timescales with modest resource requirements (mass, power, budget).

Herein we introduce a new family of compact, multispectral 3D cameras which enable and enhance lunar science and exploration on small rovers. The optical system can be readily tailored for many space and terrestrial applications requiring high precision quantitative 3D performance within a compact, low mass and rugged camera. We demonstrate this through their roles within the LUVMI-X (LUnar Volatiles Mobile Instrumentation eXtended) [1] - a lightweight lunar rover being developed to investigate traces of volatiles in regions of perpetual darkness at the polar regions of the Moon.

LUVMI-X overview: LUVMI-X (Fig.1) aims to search for water ice and other volatiles, scoping out the lunar environment in support of the aim to establish a lunar economy and future human missions to the Moon and beyond.

The rover incorporates state of the art core instruments [2,3,4] with the ability to carry customer-provided instruments (implemented as on-board payloads or deployable payloads), facilitated through the use of standardised interfaces.

Imaging systems overview: LUVMI-X includes a number of imaging systems for both mission critical and scientific functions that are shown in Fig.2. Each system connects to a central image processing unit with embedded Graphics Processing Unit that forwards pertinent and low-bandwidth data to the host computer. **NavCam (Navigation Camera)** is mounted to a pan and tilt mechanism on top of the mast allowing for imaging all around the rover. NavCam provides both context for route planning and scientific analysis through 3D measurement and multispectral imaging. Safety of the rover is enhanced by three **HazCams (Hazard Cameras)**, one to the rear for situations where the rover must reverse and two to the front acting as a stereo-bench, whose 3D information is also used to range-find and focus the laser of the VOILA (Volatiles Identification by Laser Analysis) instrument.

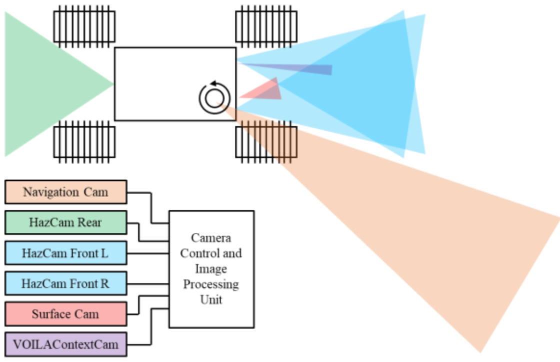

Figure 2: LUVMI-X imaging systems architecture

VOILA is further supported by a telescopic camera mounted at the front of the rover co-aligned to the laser, providing high-resolution contextual imagery of the target before and after sampling. **Surf-Cam (Surface Camera)** provides detailed multispectral 3D images and video of the rover's drill and cuttings pile as it penetrates the lunar surface (Fig.3). Illumination is provided by either white or multispectral LEDs surrounding the lens aperture. Example images from the drilling test in sand are shown in Fig.4.

Figure 3: SurfCam (Left) and SurfCam mounted below LUVMI-X rover to observe deployment of sampling drill.

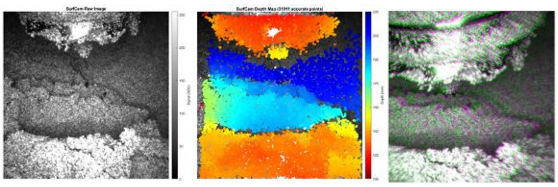

Figure 4: 2D raw image of drill retracted from sample site revealing borehole (Left). 2D image with rainbow depth map overlaid (Centre). Green-Magenta anaglyph (Right).

Light-field imagers for space exploration: Both NavCam and SurfCam employ the light-field (plenoptic) imaging technique facilitating compact, low mass, mechanically robust 3D imagers offering an extended depth of field and high signal to noise through a computationally reconstructed fast lens.

An overview of the architecture is shown in Fig.5 with the option for multispectral illumination.

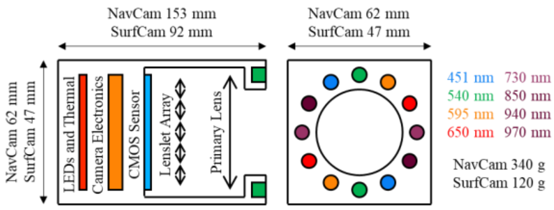

Figure 5: Architecture of NavCam and SurfCam light-field imagers with masses and dimensions.

Reflected light from the Sun or LEDs enters the camera aperture and is collected by the primary lens that is then refocused onto the CMOS sensor plane through the lenslet array. Raw images read-out through the camera electronics comprise multiple sub-images of the scene that originate from sub-apertures of the primary lens. These sub-images contain localized redundancy of scene information, as the sub-apertures are physically offset throughout the primary lens. Computer vision techniques allow features to be matched and either triangulated to provide depth information or warped with projective distortion and superimposition to increase resolution and signal-to-noise. Multiple sub-images provide multiple pairings for triangulation and in multiple orientations (compared to that of a traditional stereo-pair camera), to reduce the triangulation error and the number of failed matches that may arise from occlusion or specular reflection.

Future plans and other applications: LUVMI-X cameras will be developed by mid-2021. Selected COTS components and interconnections will be environmentally tested (T-vac, vibration, shock and radiation) during the programme to raise TRL. Additional mechanical interfaces are provided to seamlessly integrate existing space qualified components such as SpaceWire camera modules – allowing rapid progression to a full flight-ready model.

In addition to the imagers presented here, a 360-degree 3D panoramic imager is being developed to combine the functions of both NavCam and HazCams. This mast-based system requires no pan or tilt mechanisms, substantially reducing mass and complexity. Miniaturization allows for *in-situ* imaging through an instrumented lunar drill [5] to see down the borehole.

A multispectral 3D microscope SamCam (Sample Camera) [6] is being developed for the ESA PROSPECT package [7] ProsPA instrument [8] (Fig.6). An early prototype recorded video of particles moving under micro-g on a sounding rocket [9].

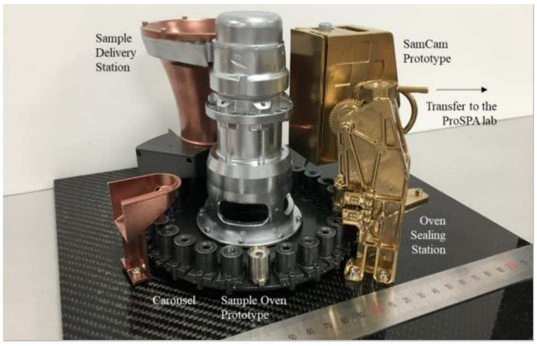

Figure. 6: Solids Inlet System model including SamCam

Conclusion: A suite of compact and versatile 3D multispectral imagers have been developed for lunar exploration. The optical system can be tailored for many space and terrestrial applications requiring high precision quantitative 3D performance from compact, low mass and rugged cameras.

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References: [1] Gancet. J. et al. (2019) *ASTRA 2019*, [2] Biswas. J. et al. (2020) *ELS2020*, LUVMI-X, [3] Sheridan. S. et al (2020) *ELS2020* VCAS and deployables, [4] Vogt. D. et al. (2020) *ELS2020*, VOILA, [5] Barber. S. et al. (2020) ELS2020, iDrill, [6] Murray. N. et al. (2020) *LPSC51*, SamCam, [7] Sefton-Nash. E. et al. (2018) *LPSC* 2740, [8] Barber. S. et al. (2017) *LPSC* 2171, [9] Miles. D. et al. (2017) *SPIE* 10397, [10] UKSA Case Study