Autonomous Soil Assessment System: Contextualizing Rocks, Anomalies and Terrains in Exploratory Robotic Science (ASAS-CRATERS). K. R. Raimalwala[1], M. Faragalli[1], J. E. Reid[1], E. P. Smal[1], and M. M. Battler[1], [1]Mission Control Space Services Inc., kaizad@missioncontrolspaceservices.com, 1125 Colonel By Drive, 311 St. Patrick's Building, Ottawa, ON K1S 5B6.

Introduction: The characterization of a planetary surface from visual imagery is a common initial step in almost every scientific investigation that may then use specialized instruments for remote sensing, contact sensing, and sample analysis. Understanding the formation and evolution of a geologic setting requires an understanding of what facies are present in the scene, their layout, geometry, density, and the contact boundaries and spatial relationships between them [1].

Mission Control is developing ASAS-CRATERS, a multi-mission technology, to address the need for automated geologic scene characterization on planetary rover missions, which can benefit a wide range of science investigations, rover navigation, and activities such as resource prospecting. It comprises algorithms for terrain classification and novelty detection using convolutional neural networks, and for data aggregation to produce relevant data products for supporting science operations. Built on cutting-edge algorithms and off-the-shelf computing components, it offers low-cost ways to speed up tactical decision-making in next-generation commercial lunar missions.

Background and Motivation:

Autonomy in Science Operations. There are several motivating factors that drive the need for autonomy in science operations. In traditional Mars rover operations, visual surface characterization and subsequent analysis and decision-making takes place in day-long tactical cycles [2]. In commercial lunar rover missions however, reduced latency coupled with shorter mission durations will require very rapid tactical decision-making processes. This means less time to analyze data, identify sites to explore, and conduct trade-offs regarding navigation.

Sensing capabilities are growing increasingly powerful but data transfer rates are not sufficiently high to downlink the wealth of scientific and engineering data generated on current or future rovers in tactical decision-making timescales. Finding novel methods in dimensional reduction that intelligently compress data while retaining the underlying key information is important for next-generation missions.

The nature of scientific discovery makes onboard autonomy compelling. Autonomous classification and novelty detection increase the chances of detecting valuable novel/sparse features (ex: outcrop on the lunar surface) that may otherwise be missed in scenarios that prioritize driving and other mission needs.

Any AI-based decision-making process onboard will likely require a semantic representation of the terrain. Soon, fully autonomous planetary rovers will perform terrain-informed and science-driven exploration, path planning, and instrument targeting, all of which will require terrain classification onboard.

Application to Lunar Geology. While dedicated science instruments that reveal mineralogical and elemental composition improve our understanding of geological processes, a rover's navigation sensors can document the morphology, morphometry and composition of surface materials, regardless of the primary investigation goals. High-resolution colour images and 3D data from stereo cameras provide information such as the size-frequency distribution and physical characteristics of craters and rocks, regolith properties, and outcrop features. All this offers valuable insight into the geologic setting. ASAS-CRATERS investigation objectives are independent of any specific mission, making the technology versatile as a payload in support of science missions. To provide a practical output as a science support tool, a classification scheme is being developed that segments a geologic scene into centimeter-decameter scale units that are visually distinct based on morphology, tone, and texture. See Figure 1 for an example.

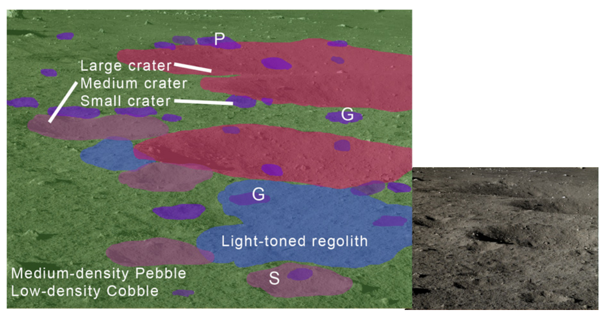

Figure 1: Hand-labelled lunar terrain classification example. Letters indicate crater degradation; P: Pristine; S: Semi-Degraded; G: Ghost. Right: original Yutu-1 image.

Technology:

Algorithms and Software. ASAS-CRATERS consists of three algorithms implemented on an embedded processor used to process imagery from a rover's navigation sensors. First, the terrain classifier consists of a deep-learning encoder-decoder style network which classifies each pixel into semantic terrain labels. Second, the novelty detector uses a semi-supervised convolutional neural network architecture with an autoencoder module and a binary classifier that work in series. Third, a data aggregator will combine the classification and novel feature outputs on a map that is useable by onboard algorithms and light-weight for more efficient downlink. Embedded software will be developed using the Flight Software Platform (FSP), a suite of flight software development tools offered by Mission Control.

Sensors and Computing Hardware. ASAS-CRATERS algorithms will be hybridized for implementation on the Q7, a high-performance, low power Xilinx Zynq Multiprocessor System-on-Chip FPGA designed by Xiphos Technologies. The Q7 mass, volume, and nominal power are 24g, 78x43x9mm, and 1W. The complete system may include additional components such as a daughtercard and connectors that will add mass, volume and power. Using off-the-shelf components will lower costs for development and enable commercialization.

Concept of Operations: ASAS-CRATERS will have three phases of operations. First, in a pre-flight training phase, the terrain classifier will be trained using relevant human-labelled images. Second, the classifier will be updated with terrain images collected *in situ* in the initial mission phase and labelled by the science operations team. The third phase consists of science operations. The tactical cycle may consist of: 1) Capture rover navigation camera images; 2) Generate ASAS-CRATERS outputs onboard and downlink; 3) Analyze outputs in the geological context of the terrain traversed thus far, including spatial distribution of terrain types and novelties detected within the scene; 4) triage targets identified by the science team based on ASAS-CRATERS outputs and other data products; 5) Uplink commands to navigate rover to target site; 6) Conduct close-up inspection, with precise maneuvering about the target, using the camera and relevant science instruments.

Use Cases. ASAS-CRATERS will benefit science missions in several ways. First, as a support tool in tactical decision-making cycles. Novelty detection can aid scientists that may miss features or spend valuable time in looking for them. The data product, a map of the traverse with information on classified geologic units, is a low-dimensional representation which optimizes downlink. The classification itself can speed up scientific analysis in rapid tactical cycles and this becomes increasingly more useful in complex scenes diverse in mineralogy and lithology. Second, for high-priority features (e.g.: novel features, specific units), it can be used by algorithms onboard to perform targeting of instruments and data triage for prioritized downlink. Third, as a semantically useful terrain representation, it can be used by advanced perception and path planning algorithms to enable autonomous and intelligent navigation.

Integration with Artemis: ASAS-CRATERS is intended to provide autonomous capabilities for lunar rovers and will be an early demonstration of advanced AI and robotics algorithms relevant for autonomy onboard crewed vehicles. Although it does not require interaction with surface crew, one benefit of crew presence is the rapid *in situ* validation of specific geologic units as observed by crew members with relevant expertise. This will expedite the pre-operational phases as Earth-based teams will be able to more confidently train the terrain classifier and novelty detector components of ASAS-CRATERS. The technology may also be used as a driver's aid tool onboard crewed vehicles for navigation or scientific observations. Novelty detection in particular may be valuable in alerting crew during driving operations when scientific observation is not the primary goal.

Field Tests and Demonstrations: The terrain classifier was first developed under the CSA-funded Autonomous Soil Assessment System project by Mission Control [3]. In 2019, it was used to classify eight Mars-relevant terrain types in real-time at ~15 FPS as the rover drove at 20cm/s (see Figure 2 for an example). This was a part of SAND-E (Semi-Autonomous Navigation for Detrital Environments), a NASA PSTAR funded project led by Dr. Ryan Ewing at Texas A&M University, which integrates robotic terrain analysis, geochemistry, and sedimentology to assess sediment transport pathways at sites in Iceland.

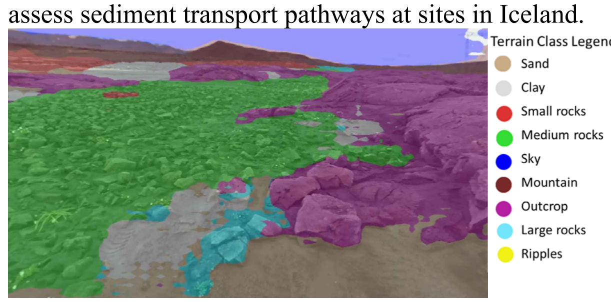

Figure 2: Classifier output overlaid on one camera image during a SAND-E traverse in Iceland field tests.

While ASAS-CRATERS is a multi-mission payload, near-term demonstrations are targeted for upcoming lunar rover missions in 2021 and 2022.

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References: [1] Francis R. et al. (2014) *SpaceOps*. DOI: 10.2514/6.2014-1798. [2] Gaines D. et al. (2016) *PlanRob*, 115-125. [3] Faragalli M. et al. (2018) *i-SAIRAS*.