RECENT APPLICATIONS OF MISSION CONTROL SOFTWARE AND VISUAL TOOLS FOR ADVANCING AUTONOMOUS AND REMOTE ROVER SCIENCE OPERATIONS.

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Introduction: In 2021 Mission Control Space Services Inc. (Mission Control) had multiple opportunities to demonstrate and test our rover-integrated software with interfaces and user tools for the scientific exploration of analog environments. These included Mars-analog volcanic terrain in Iceland, and an indoor lunar testbed ("Moon Yard") at Mission Control in Ottawa.

Mission Control has developed software for autonomous characterization of planetary surfaces called ASAS-CRATERS (Autonomous Soil Assessment System: Contextualizing Rocks, Anomalies and Terrains in Exploratory Robotic Science) [1]. During a mission, operators can use the ASAS-CRATERS software as well as other tools through our Mission Control Software (MCS) user interface (UI). This allows users to visually overlay data products on top of the primary navigation camera view. Available overlays include the ASAS Terrain Classifier, predicted hazards, distance to, rover tracks, a geometric grid, and tools for traverse planning and local mapping.

The rationale for developing and testing autonomous software, tools, and interfaces is ultimately to support mission scientists through: increasing science return of rover-based missions; and improving efficiency of remote, distributed teams working together to plan traverses, and conduct science operations.

The key outcomes from the 2021 campaigns were:

- A: Combined autonomy and science team input yielded maximum science return;
- B: Science objectives were met in scenarios with semi-autonomy (minimal human input), but data *quality* improved with increased human input;
- C: MCS and autonomy tools significantly improved mission operational efficiency.

SAND-E: SAND-E (Semi-Autonomous Navigation for Detrital Environments) is a NASA-funded project to study Mars-like volcanic environments in Iceland over two field seasons; 2019 and 2021 [2]. Six operational scenarios were compared [2] to evaluate the addition of two technologies to Mars rover operations for improved traverse planning and science decision making: autonomous terrain characterization, using Mission Control's ASAS technology, and generation of a high-resolution map ahead of the rover from a drone (UAS). The operational scenarios tested combinations of rover use with ASAS software, aerial data from a drone, and the level of human input:

- Scenario 1–rover with human input, no ASAS
- Scenario 2–rover with human input and ASAS
- Scenario 3–rover with ASAS (minimal human input)
- Scenario 4–rover plus UAS, no ASAS
- Scenario 5–rover plus UAS (human input and ASAS)
- Scenario 6–human validation team (without ASAS)

Following the 2021 SAND-E field test, the SAND-E team completed a survey to assess various aspects of the mission operations, such as the science return, decision-making efficiency, data products, task loading, and sample quality. Here, only the science return and decision-making efficiency will be explored.

Figure 1: *Example of Mission Control's ASAS Terrain Classifier output overlaid on one camera image during a SAND-E traverse in Iceland field tests.*

Science return. Here we subjectively define "science return" as the degree to which science objectives and sub-objectives were met. Nine team members ranked the scenarios from best to worst (1 to 6) based on the knowledge gained of the study site. While the responses were not unanimous, there was a consensus that scenarios 4, 5, and 6 (ranked 3, 2, and 1, respectively) provided the greatest science return. It is not surprising that the human validation team scored the highest, nor that the scenarios augmented with aerial data ranked the next highest. Scenarios 1, 2, and 3 were ranked 5, 4, and 6, respectively. Of these scenarios (that did not include humans on the ground or a UAS), the scenario that combined ASAS and human operator input ranked the highest. Based on the rankings as well as supplemental reasonings provided, there was agreement that when more information was available (i.e., UAS, ASAS tools), the better and easier it was to plan traverses to achieve a higher science return. Overall, the science return from scenarios with higher rover autonomy (minimal human input) compared with increased human input saw approximately the same number of science objectives or subobjectives being met. The main difference was in the quality of science achieved.

Decision-making efficiency. The same nine team members rated each scenario based on decision-making efficiency on a five-step scale from terrible (very slow), meh (a bit slow), good (but could be better), very good (smooth operations), and excellent (very fast). Overall, scenarios 1 and 2 were rated good, scenario 4 and 6 were very good, and scenario 3 was excellent. Each of these ratings had at least 5 responses from the team. Scenario 5 had a rating from all five options. Scenario 3 had the highest number of "excellent" ratings indicating that the ASAS software improved decision-making, especially when compared to scenario 1 and 4 where ASAS was not operated.

MCI Analog Mission: MCI (Mission Control Intelligence) was a joint lunar analog mission between Mission Control and ARL (Axiom Research Labs Private Limited, India) conducted in August 2021 at Mission Control's indoor Moon Yard. MCI utilized ARL's micro-class lunar rover which was integrated with ASAS-CRATERS software. The objective of this analog mission was to develop technology elements for surface exploration by focusing on autonomy. To assess the science return and efficiency of the analog mission, three operational architectures were tested:

- Architecture A–rover + NavCam images only
- Architecture B–rover + ASAS & MCS UI
- Architecture C–rover + ASAS + rover path planning

For all architectures common science and operational assumptions were made relating to how a thermal imager [3] would operate at the lunar south pole.

Science return. During architecture A, the science return was limited as the science team found it difficult to position the rover within a 1-2 m distance from intended targets to acquire images relying on only navigation camera images. Once overlays for NavCam images was available in architecture B, estimating distance to targets and rover navigation in general were much easier to accomplish. More distance was covered and assessment of features in the landing area was easier to determine what might be scientifically important for the mission. Due to architecture C time constraints, the science return is estimated to be comparable to B.

Operations efficiency. Efficiency of operations notably increased from architecture A to B to C, which was reflected in increased science return. Increased efficiency may have also been due to increased familiarity with the UI as the architectures progressed.

ESA-ESRIC Space Resources Challenge: Mission Control participated in the European Space Agency – European Space Resource Innovation Centre (ESA – ESRIC) Space Resources Challenge in November 2021 in the Netherlands. The goal of this challenge was to demonstrate technologies for lunar prospecting using a rover platform. The challenge included both navigational and scientific criteria to be met within the allotted 2.5-hour timeframe. For this challenge, we integrated the operation and targeting of a pan-tilt-zoom (PTZ) camera with our software.

Science return. The science objective for the challenge was to identify and characterize the composition of six rocks in the indoor landscape. The team successfully identified and visually characterized all six rocks.

Operations efficiency. Operations during the challenge were completed successfully and extremely efficiently, with 20 minutes to spare. Prior to the start of the timed challenge, the layout and specifics of the challenge were largely unknown (on purpose). The team's efficient operations during the live challenge were largely thanks to multiple training sessions and an iterative software design approach, using the rover in Mission Control's Moon Yard prior to departure.

Remote Operations for Distributed Teams: Due to travel or in-person restrictions, remote operations for testing, training sessions, or analog missions were conducted more remotely than if the same operations were conducted several years ago. For example, dozens of team members across several time zones remotely participated in and successfully achieved MCI analog mission operations, with only a skeleton staff on-site. Remote training sessions were also conducted prior to the Space Resources Challenge. Remote participation was not used during the SAND-E campaign.

Remote participants provided feedback that improved communication and identified additional tools and information to be displayed for improved remote operations. UIs were able to display the necessary information for the team to make mission decisions.

Summary: Mission Operations studies conducted during SAND-E were the most rigorous of the test campaigns discussed here, due to the field site, mission duration, and complexity of science studies. SAND-E results indicate that the combination of ASAS and science team input increased science return, and the use of ASAS and MCS UI significantly improved operational efficiency. The short durations of the MCI mission and Space Resources Challenge provided less opportunity for science return and efficiency analysis, but the different goals and conditions for all three yielded results that continue to improve MCS and autonomy features and thereby future mission operations.

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References: [1] Raimalwala et al. (2021) *5th PDW & 2nd PSIDA* #7079. [2] Ewing et al. (2020) *LPSC LI* #2857. [3] Battler et al. (2021) *LPSC LII* #2767.