RESULTS FROM THE CSA'S 2015 MARS ANALOGUE MISSION IN THE DESERT OF UTAH

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ABSTRACT

The Canadian Space Agency, in partnership with Western University and MacDonald Dettwiler and Associates, conducted a field deployment in the Utah desert in November 2015 to emulate portions of the first steps of a Mars Sample Return mission: the identification and acquisition of scientifically interesting samples.

The site was selected because of its scientific relevance to certain regions on Mars, being predominantly of sedimentary nature and preserving evidence of a previous aqueous environment. Equipment being tested at the site included the CSA's Mars Exploration Science Rover (MESR) equipped with a mini-corer and a 3D microscope mounted on a robotic arm, a suite of cameras, and a LASER range sensor.

The rover was remotely controlled over a satellite link from the Canadian Space Agency headquarters in Saint-Hubert, Canada. During the 14-day mission, the rover traversed 234 meters, acquired four samples (regolith and sedimentary material), took microscopic images at every sample location, and acquired several images and 3D LIDAR scans of the site. In addition, X-Ray fluorescence, Raman spectroscopy and X-Ray diffraction measurements were taken from hand-held instruments throughout the mission. Tubed samples have been returned to the science team for analysis, along with additional hand-collected samples from the same sites to give the science team enough material to validate its sample selection strategy.

1 INTRODUCTION

Mars Sample Return (MSR) is one of the highest priority goals of the international scientific community (e.g., [1]). Returning samples with known geological context from Mars for analysis using the best laboratory techniques on Earth is seen as a crucial step in advancing knowledge of Mars [2][3]. In addition to scientific interest, MSR will address important knowledge gaps and may aid in demonstrating key capabilities needed for human exploration.

The international priority for Mars Sample Return resulted in the International Mars Exploration Working Group (IMEWG), an agency forum for the coordination of Mars Exploration planning, commissioning the international Mars Architecture for the Return of Samples (iMARS) study [4]. The study report, published in 2008, provides an architecture concept and requirements to help agencies develop potential contributions to MSR.

In order to advance technology, science and operational readiness in preparation for an eventual MSR campaign, an analogue mission was designed and executed based on some of the concepts and requirements derived from [3][4][5].

A Mars-like environment was needed to test requirements and demonstrate capabilities under the systems engineering adage: 'test as you fly, fly as you test'. In particular, a site with lack of vegetation over long distances and relevant geology was needed to test navigation, science decision making, arm positioning, and interactions between scientific instruments.

2 MISSION DESCRIPTION

The field deployment was conducted to fulfil the following objectives:

- Test the concept of operation and selected technologies under realistic conditions to stress systems and identify their advantages and limitations;
- Validate the usefulness of the proposed instrument suite to conduct Mars-relevant science remotely and to properly select samples to be returned;
- Foster collaboration between engineers and scientists in the context of a realistic mission to better understand each other's requirements and constraints;

To accomplish these objectives, a MSR-like sample collection mission was designed. For the 2015 campaign, the strawman mission was the cache rover that selects and prepares samples to be returned by a future sample return mission.

The rover was deposited at a remote site whose exact location was disclosed neither to the operations team nor to the science team. Prior to "landing", the science team was provided with a variety of datasets similar to those that would be available for a landed Mars mission (e.g., high resolution imagery, multispectral remote sensing data). These data were used to perform a regional geological interpretation and to develop notional traverse plans to satisfy the scientific objectives.

The rover was operated from the Exploration Development & Operations Centre (ExDOC) located at the Canadian Space Agency (CSA) headquarters in St-Hubert, Canada and the science team was located in a science backroom at Western University in London, Canada.

Semi-realistic conditions were imposed on the science team and operations team. The team was limited to 6 hours of operation, 400Wh of daily energy budget and 64 000 kB of daily downlink.

The rover commands and telemetry were fed through a satellite communications link, which also imposed time delays and bandwidth limitations.

2.1. Site Selection

Determining an appropriate field site required balancing scientific and engineering test objectives while ensuring that the terrain was logistically feasible for a robotic deployment. With these considerations, a contract was issued to the Western University to identify suitable candidate North American locations. Based on the results of a literature survey, analysis of remote data, a field visit, and subsequent verification by CSA, a site approximately 10km northwest of Hanksville, Utah, USA was ultimately selected.

The stratigraphy of the region comprises primarily Jurassic sandstones and mudstones associated with the Brushy Basin member of the Morrison formation [5][7]. Scattered throughout the region are a series of linear features elevated meters to tens of meters above the surrounding terrain, formed via topographic inversion processes [8]. These so-called "inverted channels" were of particular interest as they are strongly indicative of ancient aqueous environments [9] and have been proposed to be analogous [10] to similar features previously identified on Mars [11][12][13].

The rover workspace (RWS) was located near the nose of a dissected inverted channel and extended approximately 100m in radius. Other than the inverted channel itself, local topography was extremely flat, characterized by less than 3m of elevation change over the majority of the area. The surface was almost entirely vegetation-free, and was covered mostly by loosely distributed pebble- to cobble-sized particles atop duricrust (See Figure 1).

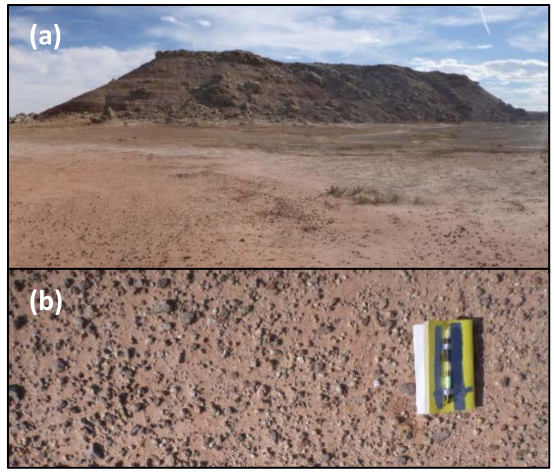

Figure 1 - (a) A view of the rover workspace, with a remnant portion of an inverted channel rising approximately 20m above its surroundings. (b) Typical surface covering of unconsolidated pebbles and small gravels. Field notebook for scale is 7" by 4" (180mm x 100mm).

Logistical requirements were also satisfied at this site. The RWS was less than 200m from an access road that was easily navigable with a cube van, facilitating transport of the rover and associated equipment to the test region. Line of sight between the truck and the RWS allowed for the development of a local communications network, with data transmitted back to the rover control station at CSA headquarters via satellite.

2.2. Concept of Operation

As with a real Mars scenario, the science team received telemetry once per day (in the evening). Each night the team prepared the next day's science plan, which was sent to the operations team in the morning. A daily teleconference was held to validate the plan before its execution by the operations team. Data volume limitations were imposed on the science team to restrict the number of science measurements and images to a realistic set. A description of the science planning cycle can be found in [14].

For the 2015 campaign, Mars-like rover navigation was not an explicit objective of the tests. Instead the communications constraints imposed on the operations team were more typical of lunar operations than Mars operations. The rover was teleoperated with time delays on the order of 1 to 2 seconds and a bandwidth of 400 kbps for downlink (from the rover to the control room) and 100 kbps in uplink. For this mission, the time delays used were those naturally present in the satellite link. No additional delays were artificially added. Operations were conducted manually by a pair of operators: a rover pilot and a navigator.

The rover pilot and navigator used several sensors to build their situational awareness. They had access to visual imagery from a stereo camera pair mounted on the sensor head. They also had access to three belly cameras used to assess obstacle size and a zoom camera to obtain high resolution images of scientific targets from a distance. In addition, a LIDAR sensor was used to build three-dimensional world models that were viewable in the operator interface.

The rover pilot was driving the rover using a joystick to send velocity commands to the rover. Even with the rich set of camera views available, it is still possible for the operators to become disoriented over long traverses. To compensate this phenomenon, the pilot often created a target feature in the virtual world at the rover's destination and used the ruler feature, which essentially stretched a string between the rover and the target destination. The pilot was able to easily find the target destination by following this string in the world model.

The placement of the instruments at the end of the arm was conducted in a two-click sequence using the Automatic Instrument Placement Tool (AIPT). The operator would pick the instrument placement location in the 3D world model. The first command was used to position the arm in hover mode at a location automatically calculated above the target and the second command was used to bring the instrument in contact with the target.

These operator aids proved adequate to conduct operations under the constraints imposed for this mission.

2.3. Experimental Set-up

The integrated system that was used during operation consists of the Mars Exploration Science Rover (MESR) equipped with the Small Manipulator Arm (SMA) used to position the Three Dimensional Exploration Multispectral Microscopic Imager (TEMMI) and a Mini-Corer. This integrated system was controlled by the engineering team through the use of the Apogy [15] ground control software. Apogy was also used to collect the instrument telemetry and science data and to provide a basic Geographic Information System (GIS) to maintain spatial and temporal context information.

The MESR is a 6-wheeled rover with all-wheel drive. The four corner wheels are independently steerable. The passive walking beam suspension provides platform stability and obstacle climbing capability. The fully equipped rover weighs close to 360 kg.

The MESR is equipped with a mast located at the front of the vehicle. This mast is equipped with a pan-tilt unit (PTU) that can orient the sensor head. The sensor head, about 1.7 m above ground, contains a stereo-camera used for navigation and a zoom camera used for high resolution imaging. The pan axis also supports a SICK lidar. This arrangement allows 360° imaging of the rover surroundings in 3D and provides panorama imaging capability.

The Small Manipulator Arm is a 6-joint manipulator that includes a vision system used to survey target sites for later observation or drilling. It is used to position TEMMI and the Mini-Corer on the ground or on rocks close to the rover.

The SMA end-effector can be positioned relatively precisely (within a few millimeters) but its mounting location on the front right side of MESR adds constraints to the workspace reachable by SMA for the payloads.

TEMMI is a microscope imager that is mounted on the end effector of the SMA. The latter is used to position TEMMI close or in contact with a rock sample to image. It is a sophisticated instrument that supports many advanced features, such as focus stacking imaging or 3D surface reconstruction. Unfortunately, because of resource constraints, the multi-image stacking capability was not available during the 2015 tests. Given the limited focus stage travel and depth of field of the microscope, the TEMMI baffle must be in contact or very close to the rock surface in order to get a clear image.

The Mini-Corer is a rock coring drill that can acquire rock cores and soft soil samples. It can also be used to abrade rock in order to expose pristine surfaces for inspection by TEMMI.

The Mini-Corer can acquire cores of 10mm diameter and 50mm length from solid rock using a coring bit. It can also collect loose soil sample using a push tube. As its name implies, the push tube is a hollow cylinder that is pushed through the ground (with or without rotation and percussion) to acquire a soil sample.

3 RESULTS

This section provides a detailed day-by-day description of the analogue mission as well as a synthesis of the outcomes.

The mission started on November 11st 2015 (Sol 1) with MESR located onto its lander mockup (see Figure 2).

Under direct teleoperations from CSA Headquarters, the rover egressed and traveled about 26 m to reach a rock outcrop (named Alfheim) that had been selected by the backroom scientists on the previous day. Once at the target, zoom images were acquired to prepare contact science measurements for the next Sol. A LIDAR scan of the outcrop was also requested by the scientists but the rover operators were unable to collect the scan due to a sporadic failure of the sensor head pan unit. That issue is discussed at the end of this section.

Figure 2 MESR onto its lander on Sol 1

On Sol 2, the rover was repositioned to bring the rock outcrop within the Small Manipulator Arm (SMA) workspace. Next, a TEMMI image of the outcrop was acquired (Figure 3 and Figure 4), and several hand-held science measurements were made (i.e., X-Ray Fluorescence (XRF) and Raman spectrometers). A drill site was selected by the science team, and the mini-corer was placed into the appropriate position. To preserve schedule, however, the solid rock core was extracted manually using a hand-held drill.

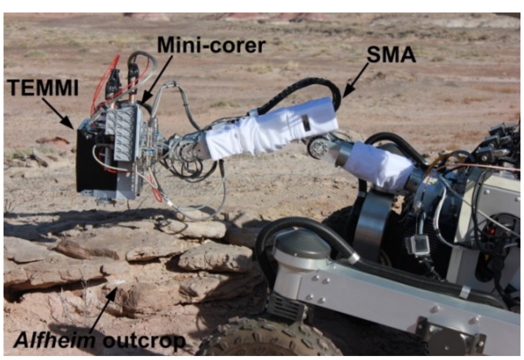

Figure 3 Execution of the TEMMI placement onto the Alfheim rock outcrop

On Sol 3, the rover operators stowed the arm and took a zoom image of the hole left by the sample extraction on the rock. The rover was then teleoperated to the next geological target (named Lfing), located 70 m away. Once at Lfing, a panoramic image and a LIDAR scan were acquired. Based on Sol 3 data, the scientists decided to analyze a large rock (Idi) that was located 12 m away. Consequently, on Sol 4, the rover was driven to Idi and several instrument readings were collected at this location (i.e., panorama, LIDAR scan, zoom images, XRF and Raman). The objectives for Sol 5 were mainly to bring the Mini-corer in contact with Idi and then to take a core sample as well as science measurements. After a few attempts, the rover operators decided to abort the placement of the Mini-corer because the arm was reaching joint limits. Despite the fact that a failure on the instrument placement would fail the entire science data acquisition for that sol in a real mission, it was decided to collect the science hand-held measurements and carry-out the manual core extraction so as not to impact on the student geology training aspect of the analogue mission.

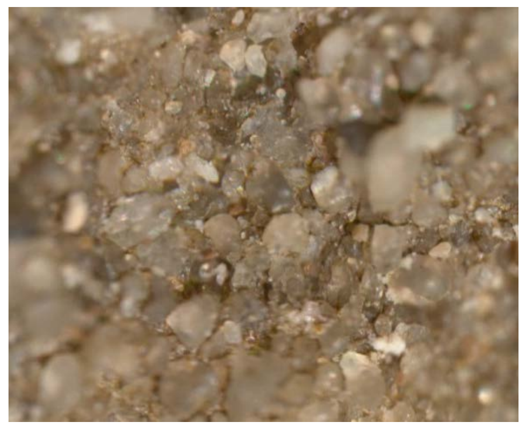

Figure 4 TEMMI image acquired on Sol 2

Sol 6 began with the acquisition of additional XRF and Raman measurements on Idi. Then, the rover traversed approximately 15 m to reach an area of interest where XRF and Raman data were collected, as were belly camera images. The rover traveled another 15 m to reach a second area of interest (Olaf).

On Sol 7, XRF and Raman measurements were taken at Olaf location. The rover was then teleoperated to Heimdall area of interest which was about 18 m away from Olaf. At Heimdall, imagery and a LIDAR scan were acquired. On Sol 8, additional XRF and Raman data were collected at Olaf and at a location named Modgud which was 12 m away. At Modgud, a zoom image and a LIDAR scan were acquired and the rover was positioned to allow contact science on the next sol.

The main objective on Sol 9 was to place TEMMI and the Mini-corer in contact with a precise location (named Mist) on a slope selected by the scientists. To do so, the operators used the Automatic

Instrument Placement Tool (AIPT). The latter brought TEMMI in contact with Mist. The image was taken but it was out of focus and therefore unusable by the scientists. It was found that a corner of the TEMMI body was in contact with the slope leading the microscope aperture to be slightly off the target hence an acceptable image focus was impossible to get. Figure 5 shows the improper TEMMI configuration with respect to the slope.

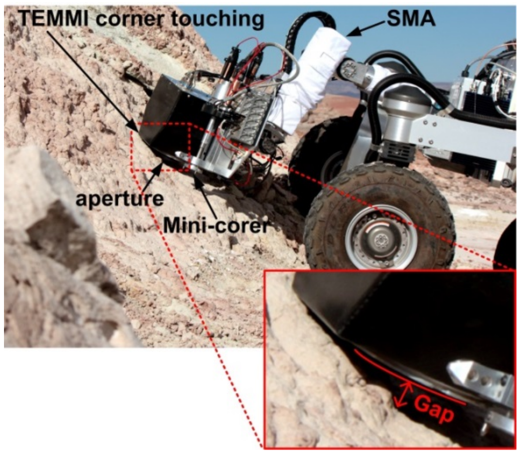

Figure 5 Improper TEMMI placement onto Mist target. The zoomed image shows the gap between the TEMMI aperture and the target.

The operators manually brought in contact with Mist the Mini-corer push tube and initiated the soil sampling process. It took less than 10 minutes to successfully extract the soil sample. Then, the SMA was stowed to allow for the hand-held science measurements (XRF and Raman).

On Sol 10, the rover traveled approximately 6 m from Mist and took a zoom image of the hole left by the previous sample extraction. The rover then resumed the traverse to a further waypoint (namely Fimbulvetr) that was 60 m away. Once at its location, several datasets were collected (i.e., XRF, Raman, LIDAR scan, belly cam, panorama).

The Sol 11 objective was to take a TEMMI image and extract a soil sample of Fimbulvetr. The placement of TEMMI and the Mini-corer was carried out using the AIPT. Both TEMMI and Mini-corer operations were successful. The SMA was stowed and post-drilling zoom images were taken. Finally, XRF and Raman measurements were taken at Fimbulvetr which concluded mission operations.

Figure 7 depicts the total path traveled by the rover as well as the rover location at the end of every sol. The total distance traveled was 234 m over 11 command cycles which represents an average of 21 m per command cycle.

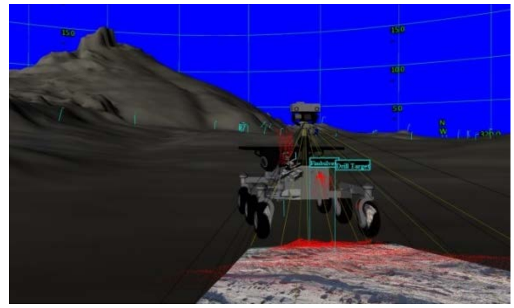

Figure 6 Apogy 3D render showing a zoom image projected onto the DEM and superimposed with a LIDAR scan (red dots). Flags show the name of the area of interest and the location that the AIPT had to track.

In the past, the team has carried out other field trials for which the emphasis was on the navigational aspect of the mission, which correspondingly resulted in a much higher distance traveled per day. In the case of the mission outlined in this paper, the focus was more on the contact science tasks involving robotic placement of instruments. Those types of placement tasks are time consuming and not trivial to achieve.

Even with the challenges of instrument placement and rover positioning, operations were conducted much more rapidly than would have been on a landed Mars mission. The Curiosity Rover, for example, can take several weeks to interrogate an outcrop, position the rover, and collect a sample. Given the relatively short duration of our deployment, several operational and scientific decisions were accelerated.

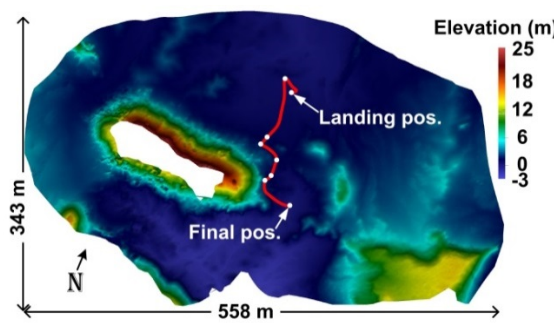

Figure 7 Overview of the path followed by MESR onto the DEM colored by elevation. White spots are the rover position at the end of every sol.

The infrastructure and the robotic setup outlined in Section 2.3 have successfully supported the MSR analogue mission as planned. One of the objectives of the mission was to validate the operator assistance tools developed in the Apogy [15] ground station for driving the rover, placing the arm and interpreting science data. The remote scientists did use Apogy to plan the daily activity sequences as well as to put all the data in a common reference context. Table 1 lists all data product collected by the rover and delivered to the scientists during the mission.

Table 1 List of data product acquired and delivered to the scientists. The instruments in parentheses are those not integrated with the rover (hand-held)

Instrument	**Nb of data product acquired**
TEMMI image	2 (plus 1 out of focus)
Push core sample	2
(Drill core sample)	2
LIDAR scan	8
Belly cam image	30
Zoom image	25
Panoramic image	7
(XRF measurement)	33
(Raman measurement)	32

At the start of the mission, some difficulties were encountered due to failures that were caused by transportation of the equipment to the sire.

The main failure happened in the pan unit that is used to rotate the sensor head. This was a major issue since important mission data could not be taken without a functioning pan unit: LIDAR and panoramic scans as well as the zoom imagery require this functionality. A temporary fix was implemented in the field to allow the execution of the mission but the unit was still sporadically unstable over the entire mission. The defective unit will be replaced before the next deployment.

4 LESSONS LEARNED

This was the first integrated test in a remote desert site for the MESR rover and associated payloads. As the mission progressed, a significant list of lessons learned was put together regarding hardware, logistics and operations. In general, all objectives of the mission have been met: the concept of operation was tested under realistic conditions, the usefulness of the suite of science instrument was validated and the science and engineering teams worked in close collaboration.

The science planning tools provided by the Apogy software were appropriate for preparing science plans based on a one-cycle-per-day approach such as is expected in a typical Martian mission. The operator assistance tools to navigate and pilot the rover (also provided in the Apogy framework) have been demonstrated to work for teleoperation under conditions more typical of lunar operations. The rover driving aids were quite mature since they had been tested through several field tests in the past.

However, arm placement was extremely challenging given the bulkiness of the end-effector. For example, it was virtually impossible to properly position the arm using only camera views. The superposition of camera images, with LIDAR data and projection in a 3D model was very important and was quite efficient. In the future, the AIPT needs to be modified to take advantage of the six degrees-of-freedom of SMA and to deal with arm workspace limitations. This is important especially in the case of the TEMMI which has a large aperture that must lay flat on its target. Operations in the desert of Utah in November also introduced environmental challenges. The equipment used in this campaign was built using Commercial-Off-The-Shelf equipment, and is typically operated under relatively benign weather conditions. Nights were sometimes very cold and the weather could be quite humid at times. Keeping the equipment within appropriate thermal and humidity ranges was a logistic challenge.

Another important set of lessons learned was associated with the logistics of travelling to this site. A cube truck showed to be a simple and efficient approach: the truck being used as the local command centre for the duration of the mission. However, crossing a border with sophisticated equipment was significantly more complicated than anticipated. Having local contacts at the site proved to be an invaluable help.

5 CONCLUSION

The CSA conducted an analogue mission in the Utah desert in November 2015. The mission emulated portions of the first steps of an MSR mission, and was based on the concepts and objectives outlined by the international planetary exploration community.

Equipment being tested at the site included the CSA's MESR rover equipped with a mini-corer and a 3D microscope mounted on a robotic arm, a suite of cameras, and a LASER range sensor.

The rover was remotely controlled over a satellite link from the CSA headquarters in Saint-Hubert, Canada. During the 14-day mission, the rover traversed 234 meters, acquired four samples (regolith and sedimentary material), took microscopic images at every sample location, and acquired several images and 3D LIDAR scans of the site.

In addition, XRF, Raman spectroscopy and X-Ray diffraction measurements were taken from hand-held instruments throughout the mission. Tubed samples have been returned to the science team for analysis, along with additional hand-collected samples from the same sites to give the science team enough material to validate its sample selection strategy.

A second campaign is planned at the same site in November 2016 and it will be conducted under conditions even more representative of a Mars mission. The rover pilot and operator will only have one or two windows of opportunity to communicate with the rover, who will have to execute the day's operations plan in a fully autonomous manner.

Two distinct missions will be tested using the rover. The first will be a continuation of the science mission started in 2015: the rover will be positioned exactly where the mission ended in 2015. Science data and samples will be collected for one more week. The second mission will be a fetch rover mission where the rover will navigate to a cache location to recuperate a set of sample tubes. The tubes will be collected and then returned to the lander where they will be inserted into a Mars Ascent Vehicle mock-up.

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