Lunar Rover Remote Driving using Monocameras under Multi-Second Latency and Low-bandwidth: Field Tests and Lessons Learned

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Abstract

This paper outlines the *Teleoperation Robotic Testbed* (TRT) project, which aims at testing simple concepts of operation (ConOps) for remotely driving a rover on the Moon, under a constrained Earth-Moon communication link. The ConOps under study focuses on teleoperating a rover with very little onboard autonomy, with ground operators actively and continuously involved in the control loop. The remote control station features enhanced situational awareness tools such as predictive displays, overlays on imagery, rover trajectory plot and panoramic imagery. The main source of feedback to the operators were monocular cameras and a basic localization system that were integrated on the TRT rover. During the 2013 field testing season, the TRT was deployed in many planetary analogue sites in order to exercise the ConOps. A total of sixteen teams remotely operated the TRT rover, taking turns on three-hour driving missions and traveled a total of 5.8 km over 48 hours of operation. The results of the campaign suggest that the ConOps studied might support simple lunar driving tasks. However, the rover average speed would be low (around 2 to 4 m/min), resulting from the rover being stationary most of the time, moreover, fatigue would prevent the operators from supporting long uninterrupted operations.

1 Introduction

The recent landing of the Chinese *Yutu* lunar rover has captured the public attention for the exploration of the Moon. This reminds us that the exploration of our closest celestial neighbor remains a formidable challenge, likely to be pursued for decades. In preparation for future potential missions to the lunar surface, the Canadian Space Agency (CSA) is conducting various relevant activities. Among those, one of the topics under study has been the concept of operations (ConOps) for the Resource Prospector Mission (RPM) [3]. That mission requires driving a rover in a moon polar region over a few days, in order to study lunar volatiles and perform an In-Situ Resource Utilization (ISRU) demonstration. Although the Moon is relatively close to Earth, such teleoperations are impeded by communication constraints such as delays, low bandwidth and dropouts. As pointed out by Sheridan [11], depending on the implemented ConOps, an overall position control loop is being closed by operators on Earth. The induced delays undermine the position control loop stability, and the limited and discontinuous nature of the data increases the operators' tasks complexity.

The project described herein aims at testing a simple ConOps to teleoperate a lunar rover under realistic communication constraints, i.e., delays of 10 s round-trip and a maximum download bandwidth of 300 kbps. These constraints were selected based on the expected RPM mission communication's link capabilities. The following driving modes were selected to control the rover: 1) *Rate-command* mode: the ground operator uses a hand-controller to send rate commands (linear and angular velocities) to the rover, and 2) *Position-control* mode: the operator sends desired waypoints, within a few meters from the rover location, for the rover to track. To support the ConOps, the rover was fitted with a simple set of onboard sensors, namely four monocameras and a basic localization system. The main objectives of this project were:

- to quantify the effective average speed that a rover operated using the above-mentioned driving modes might reach on the Moon, and
- to generate lessons learned regarding the onboard sensors suite and ground tools used to support the ConOps.

The contribution of this paper lies in the size of the experimental sample. The proposed ConOps was extensively tested in many different analogue sites. At the end of the testing campaign, the rover cumulated 5.8 km of travel over 48 hours of operation, remotely controlled via the constrained communication link. The sixteen teams of operators that participated to the project came from various professional background, including CSA space robotic operators and engineers, space industry rover developers, planetary scientists and a Canadian astronaut.

This paper first presents a brief background on rover teleoperation strategies that are applicable to the exploration of the Moon. Then, the system architecture and the ConOps implemented are outlined in Section 3. Section 4 tackles the field testing campaign including the results, the analysis and the lessons learned. Finally, Section 5 brings a little perspective to the project by comparing with some of the results acheived by the Luna 21 (Lunokhod 2) mission to the Moon.

2 Background

Sheridan has depicted the teleoperation of a space robot from Earth as a control problem [11]. The operation of a lunar rover implies that a control system is used to bring the rover to operator-specified locations. The resulting position control loop is closed on Earth when visual cues or other target-related information are used by the operators to send the driving commands required to reach the desired positions. The latter approach can suffer from control instability due to the data transmission delays induced in the position control loop. From basic control theory, it is known that even a small delay in a control loop can make an a priori stable system become unstable and unusable, depending on the system gain and various other factors. An intuitive strategy used by operators to deal with the delay is to drive the rover under a "*move and wait*" approach, waiting for things to "stabilize" between small displacements. This driving strategy might not be the most efficient way to conduct such operations because the rover ends up being stationary most of the time. A classic method to overcome that problem is to implement a predictive display, as proposed by Bejczy et al. [1]. The latter technique tries to minimize the impact of the communication delays by simulating a "*phantom rover*" that anticipates the real rover motion that will result from the operator's commands. Thus, the operator drives a virtual rover, in near real-time, against the delayed rover imagery. Under the context of lunar rover exploration, two predictive displays were tested by other authors [9]. Under that study, twelve different operators drove a rover through obstacle courses. The paper reports that both predictive displays significantly improved performance in terms of time taken to complete the courses. A predictive display may therefore be a useful operator tool, leading to a significant performance improvement. In order to achieve such improvement, an accurate predictive model should be available [10]. However, properly modeling the motion of a rover traveling on a rough terrain is a complex undertaking.

Another way to solve the instability problem of teleoperation under delays is to close part of the control loop on the rover. The operators can then either send a single position or a list of waypoints, and the rover tracks these commands and closes the loop using its onboard localization system. The operator closes the higher level loop to bring the rover to the global destinations. This approach makes the concept of operation more resilient to communication link constraints, but requires additional onboard capabilities (e.g., localization and path-tracking systems). A more sophisticated approach has been proposed by Kunii et al. [8], where the path planned by the operators is modified by the onboard software in order to adapt it to the new rover's observations, which are not delayed. Krotkov et al. [7] propose what the authors refer to as the *safeguarded teleoperation*, where the control of the rover is shared between the untrained operators and the onboard autonomy software. On benign terrains, the operator has full control over the rover motion, while hazardous situations will trigger the onboard software to override the operator's commands to ensure a safe drive. Fong et al. [4] extended the concept of *safeguarded teleoperation* to any operators (trained and untrained). While improving performance, those *safeguarded* approaches involve complex onboard autonomy systems. As such, they are not well suited to the scope of the work presented here, which aims at keeping onboard systems simple.

Yet, only three uncrewed rovers have successfully traveled on the surface of the Moon. The Chinese Yutu rover is the most recent example. Unfortunately, at the time of writing this paper, very little information regarding the actual ConOps used for Yutu could be found. In the 1970's, the Soviet's Lunokhod 1 and 2 were teleoperated from Earth. The ConOps for these missions was simple and no onboard autonomy was being used. The operators drove the rovers based on images coming from 5 monocameras and used hand-controllers to send commands. The image refresh rates were on the order of 1 image/20 s (Lunokhod 1) and 1 image/3 s (Lunokhod 2). Adding to the challenge of this communication latency, it was reported that the lack of contrast featured by the images made the terrain assessment difficult to conduct [5]. Nevertheless, both missions ended because of thermal issues and not because of a driver error. The *Lunar Reconnaissance Orbiter*'s imagery recently confirmed that Lunokhod 2 traveled about 42 km on the Moon, which is the longest distance driven to date by a rover on another planetary body.

3 System Architecture and ConOps

This section details the system architecture, including the rover and its sensor suite, the ground Remote Control Station (RCS) and the ConOps. The system evolved following lessons learned throughout the project. Presented here is the latest system configuration that was tested in the field.

3.1 Rover

To support the study, the CSA Teleoperation Robotic Testbed (TRT), shown in Figure 1, was used. The core rover, a CSA Juno [6], is equipped with three wide angle cameras (145° horizontal field-of-view): two looking downward for situational awareness around the rover (Left and Right cameras in Figure 1) and one pointing forward for driving (Front camera). A pan-tilt-zoom camera (PTZ cam) is also centrally mounted on the rover mast. The PTZ camera can provide a full 360° view and is controlled by the operator. A pair of stereo cameras is also installed. The latter was included into the experiment in order to collect data for future work. Finally, a Real Time Kinematic Differential GPS system is installed on the rover to independently log the ground truth data for post deployment analysis.

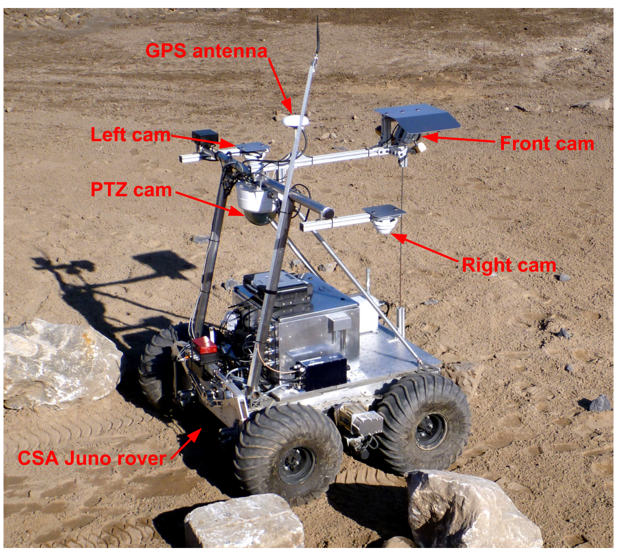

Figure 1. CSA's Teleoperation Robotic Testbed

The TRT has a basic onboard relative localization system that fuses data from an Inertial Measurement Unit (IMU) and the wheel odometry, in order to estimate the relative 3D rover pose. The rover is also able to track waypoints or paths by using a path-tracker algorithm to close a position control loop on the localization estimation. The operators make use of two modes to drive the rover:

- ***Rate-command*** mode: the operator uses a hand-controller to send linear and angular velocities to the rover;
- ***Position-control*** mode: the operator sends desired position and orientation to the rover, within a few meters from the current location of the rover. The rover's onboard path-tracker maneuvers the rover to the desired pose.

3.2 Remote Control Station: *Symphony*

Figure 2 depicts the RCS, based on CSA's *Symphony* framework deployed in a control room located at CSA's headquarters. The driver interface is composed of two screens (left hand-side in Figure 2). The upper left screen contains the PTZ view, including a crosshair type angle overlay, as well as a virtual horizon showing the rover's attitude. The lower left screen contains the Left, Front and Right camera views, fitted with distance overlays to facilitate the distance estimation process. In order to stay within the allocated bandwidth, these camera views are updated at 1 Hz and the image resolution is 320×240 pixels (except for the PTZ view which is 640×480 pixels). The Front view can be used by the driver to generate a list of waypoints for the rover to track, by clicking in the view. The Front view also includes a predictive display to be used in conjunction with the hand-controller. The predictor estimates the position and orientation of the rover, based on the operator's commands and the communication delay. The right-hand side of Figure 2 depicts the navigator interface. The upper right screen is a dashboard containing the general telemetry and commands (T&C) display. On the lower end of that screen is the PTZ T&C. The bottom right screen displays the Digital Elevation Map (DEM) of the terrain being explored, superimposed with the rover trajectory as estimated by the onboard localization system.

4 Field Testing Campaign

4.1 Preliminary Deployments

From April to August 2013, several deployments were carried out. The objectives of these testing campaigns were to collect preliminary results and lessons learned, in support of the main field deployment that took place in the fall of 2013. It is to be noted that for all deployments reported in this paper, care was taken to ensure that the operators would not see the deployment site prior to the deployment. The following subsections briefly outline the three major preliminary testing activities.

4.1.1 UTIAS Mars Dome

In April 2013, the TRT was deployed at the University of Toronto Institute for Aerospace Studie's (UTIAS) Mars Dome. The site is an indoor facility featuring a circular workspace of 40 m in diameter, used to test planetary rovers. During a three-hour mission, a CSA mission controller teleoperated the TRT from the CSA's control room, communicating with the rover over the Internet. The communication delay ranged from 1 s to 5 s round-trip. The mission objective was to bring the rover to multiple *features of interest* using only the *Rate-command* driving mode. Figure 3 shows the TRT rover approaching a feature of interest. For that first test activity, the control

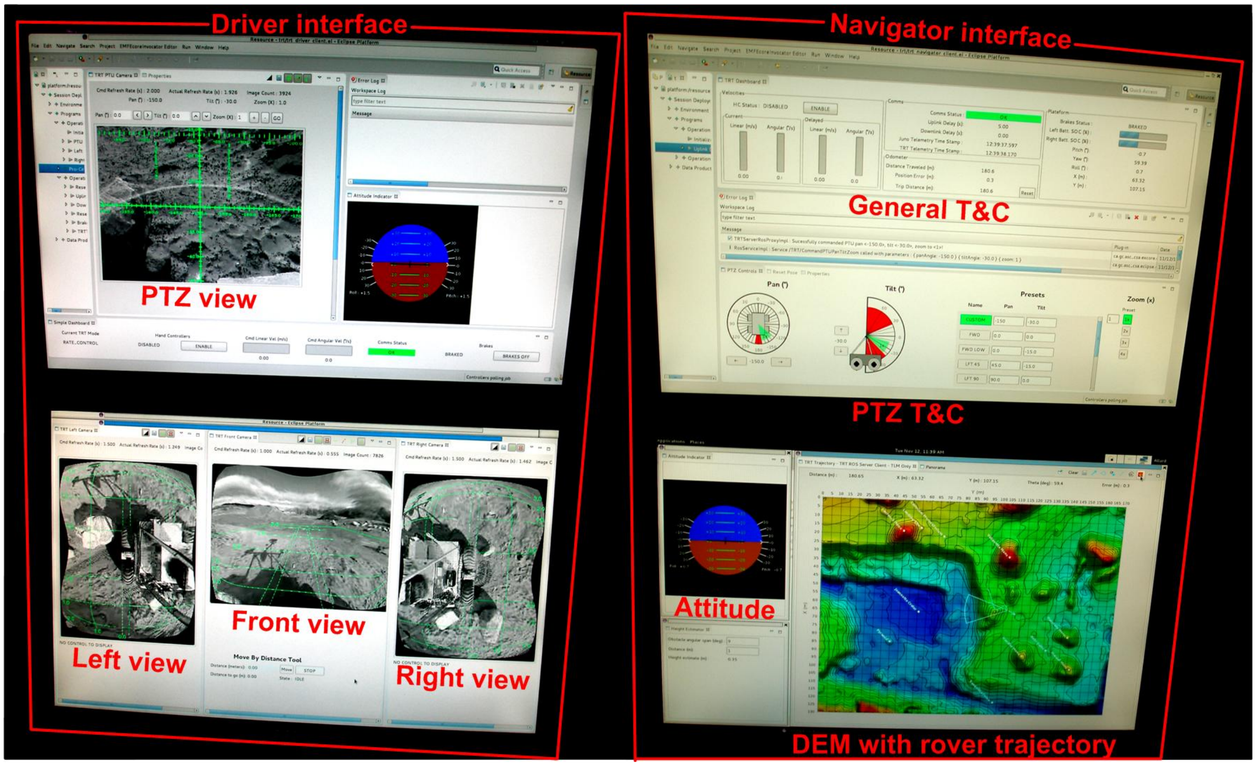

Figure 2. TRT Remote Control Station used during the main deployment

station featured a minimum set of features to the operator, namely: delayed camera views and basic telemetry. Overall, the rover traveled 139 m during that deployment. The following lessons were drawn from the UTIAS Mars Dome deployment.

1. The communication delay has a significant impact on the average rover speed (4.3 m/min average speed for 1 s delay; 1.9 m/min for 5 s delay).

2. Driving, monitoring the telemetry and estimating the localization concurrently proved to be challenging for a single operator.

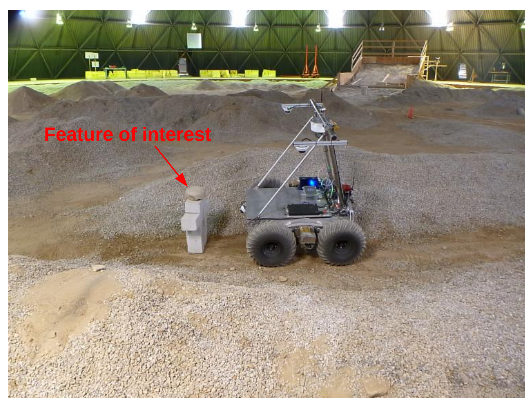

Figure 3. TRT deployed at the UTIAS Mars Dome

4.1.2 HI-SEAS

The Hawaii Space Exploration Analog and Simulation (HI-SEAS) is a Mars analogue habitat simulation funded by NASA. The isolated habitat is located on the Mauna Loa volcano, culminating at around 8000 feet above sea level. This simulation is a research project mainly focusing on crew cohesion, roles and function for long-duration space missions [2]. In July 2013, for two half-days out of their four-month journey in the habitat, five members of the HI-SEAS astronaut crew teleoperated the TRT. The rover was deployed at the CSA Analogue Terrain (AT) while a portable RCS had been sent to the habitat. The CSA AT is an outdoor test site of 120 m per 60 m that reproduces the challenging topography of a planetary body such as Mars or the Moon. Figure 5 shows the CSA AT. The communication link between the habitat's control room and the rover was provided by NASA's Space Network Research Federation (SNRF) network. The operators did not get any training with the TRT system prior to this deployment. At the end of the mission, the rover had traveled about 150 meters, representing about half of the mission planned. The CSA objectives for this activity was to assess the ability of untrained operators to use the RCS and to gather external feedback on the system from people outside the project. The main lessons learned from that deployment are listed below.

1. The RCS was complex to use from the untrained operator's point-of-view.
2. The rover configuration with two cameras pointing downward (Left and Right cam in Figure 1) demonstrated its usefulness, especially in a narrow pass, not much wider than the rover.

Figure 5. CSA Analogue Terrain

Prior to shipping the portable RCS to the HI-SEAS crew, the whole mission had been beta-tested at the CSA with the collaboration of Canadian astronaut Jeremy Hansen, acting as the rover operator. Mr Hansen had successfully carried out the three-hour mission by himself, without incidents.

4.1.3 Private Sand Quarry

In August 2013, CSA organized a deployment of the TRT in a private sand quarry located close to the CSA's headquarters. This deployment was the first attempt to formally assess the *Rate-command* concept of operation. That assessment relied on the support of four teams of operators, tasked to execute the same scenario consisting of a three-hour driving mission. More or less half of the individuals involved as operator were robotics engineers, while the others were space system operators or mission controllers. Each team was composed of a rover driver and a navigator. The driver's task was to safely maneuver the rover, while the navigator was in charge of localizing the rover using the map and guiding the driver toward the mission goals. One week prior to the deployment, every driver attended a 3 hours training session. The session included a familiarization session with the rover and a driving mission from a control room.

This deployment of the TRT spanned five days. Three teams were able to execute the mission during the dedicated three hours, while the weather prevented the fourth

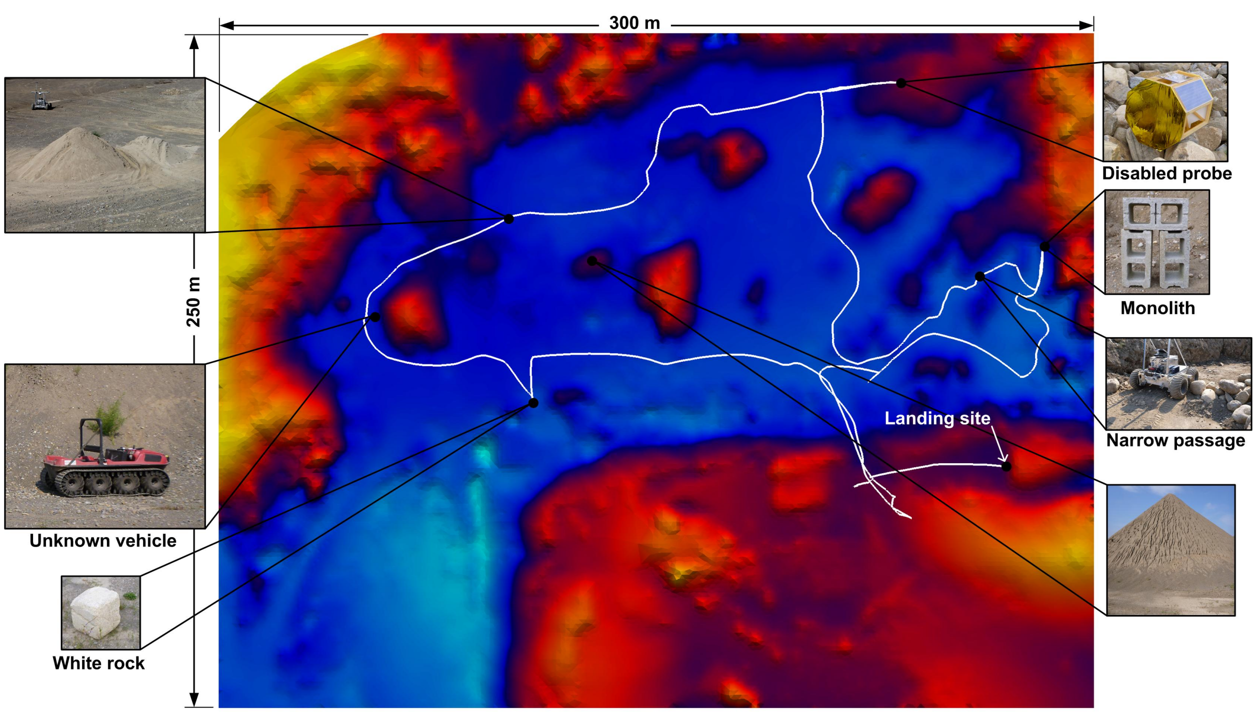

Figure 4. Overview of the August 2013 mission accomplished in a private sand quarry. The map is color-coded by elevation (highest elevation point in yellow is 17 m above the lowest point in dark blue). The white line is the GPS track log of one of the four teams. The features of interest that the teams had to find are shown in the labelled pictures.

team to complete their mission. On average, the operators were able to move the rover at 4.4 m/min, including the time when the rover was stationary (which represented about 60% of the time). During that week, the rover traveled 2.2 km in teleoperation under a constrained communication link. The emulated delay ranged from 6 s to 10 s round-trip, and the download bandwidth limit was set to 300 kbps. Figure 4 shows an overview of the mission. The main lessons learned are listed below.

1. For this deployment, no onboard localization was available. Conclusion was that localizing the rover only from the video feeds was difficult for the operators.
2. A predictive display was useful in assisting the operators adapting to the communication delays.

4.2 Main Deployment

The preliminary deployment at the private sand quarry had been conducted on a surface that was relatively flat and probably not analogous to the Moon. Performing the testing on a benign terrain might have biased the analysis. A clear limitation that had also been identified was the lack of any onboard localization system. Such system would usually be implemented on any flight rover, and not having it might therefore negatively bias the evaluation of the ConOps. Those lessons learned suggested that another deployment would be needed to fairly assess the ConOps based on the *Rate-command* mode. As a result, a major deployment was organized in the late fall of 2013. That main deployment was aimed at formally assessing the ConOps, including both driving modes, i.e., *Rate-command* and *Position-control*.

An area of another private sand quarry (Final test site) was reserved for two weeks to support that main deployment. The Final test site was modified to make it more representative of a lunar environment. The weeds were removed, many rocks (from cm to meter scale) were spread out and the ground was significantly reshaped in some areas. Figure 6 shows a panorama of the Final test site. For this deployment, nine teams were assembled: some composed of engineers from industry and some from CSA. The selected operators were either robotics engineers, planetary scientists or engineers with extensive experience in space operations.

Three weeks prior to the deployment, each driver and navigator participated to a three hours training session at CSA. Training included a familiarization with the control station tools as well as various precision drive exercises and a short simulated mission. An important objective of the training was to make sure that the operators understood the capabilities and limitations of the ground tools.

4.2.1 Mission Overview

In the test area, a landing site and a set of features of interest were defined. The mission objective was to bring the rover close to each feature of interest.

Figure 7 summarizes the mission. The total distance to travel was on the order of 600 m. A detailed mission plan was distributed to the operators 30 minutes before the start of the mission. The communication delay was 10 s round-trip and the maximum download bandwidth was 300 kbps. For safety reasons, on-site personnel monitored the rover behavior throughout the mission. A safety officer had the mandate to intervene with a remote emergency stop if deemed necessary, in situations that could yield to potential damages or injuries. Every time the e-stop would be depressed, a strike would be declared and the mission would be declared over after two strikes. Such penalties were implemented to encourage the safety over the speed of the rover, thus making the mission more analogous to an actual mission to the Moon.

4.2.2 Results and Analysis

The Arroyo is a very narrow channel not much wider than the rover, thus making this section the most challenging of the mission. Overall, five teams successfully travelled through the Arroyo. On average, the successful teams took 48 minutes to overcome this challenge. Only one team navigated through the Arroyo without committing any driving fault, mainly using the *Position-control* mode only. Figure 8 shows the Arroyo from the rover's

Figure 6. Final test site with TRT rover

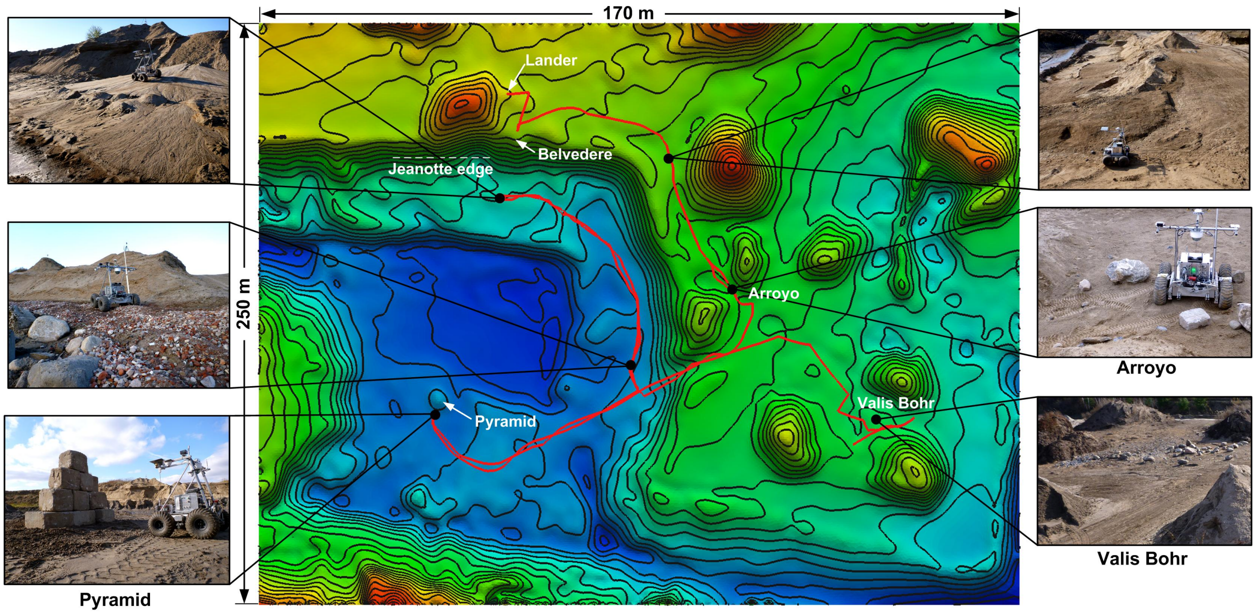

Figure 7. Overview of the mission that was conducted during the main deployment. The red line is a GPS track log collected during one of the missions.

Left and Right cameras. Markers are added to emphasize the rocks located in the rover's surroundings. Another image of the Arroyo is presented in Figure 7.

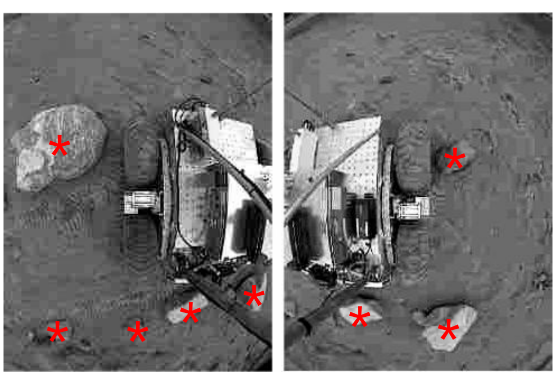

Figure 8. Left and Right camera views during the passage of the Arroyo

Table 1 presents a summary of the results. On average, the rover was stationary three quarter of the time (75%). The average speed, which is one of the principal outputs of this project, was 2.7 m/min. It should be noted that the operators were free to select the driving mode and switching between the two modes during the mission. A relation was noticed between the total distance traveled by the rover and the *Rate-command* ratio, referring to the proportion of the distance traveled under the *Rate-command* mode, as shown in Figure 9. One of the findings is that the total distance traveled is proportionally increasing with the usage of the *Rate-command* mode. The maximum distance has been achieved by the team preferring the *Rate-command* mode. No other significant correlation has emerged from the analysis of the results. However, it is to be noted that two teams were particularly careful (0 strike) and were both operating with the *Position-control* mode. Another important point to report is the significant operator fatigue after the mission as some of the team showed a high level of fatigue after the mission. This seemed to be particularly true for the driver.

Table 1. Main deployment result summary

	Average	Standard dev.
Speed (m/min)	2.7	1.0
Stationary ratio (%)	75	9
Distance traveled (m)	287	137
Number of strike	1.0	0.9
Rate-command ratio (%)	20	20

4.2.3 Lessons Learned

After the mission, most of teams provided an exhaustive list of lessons learned and recommendations for future works. The following is a summary of the principal lessons learned which are applicable to the concept of operation.

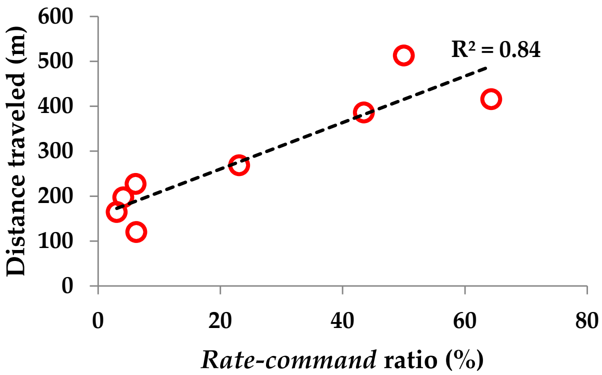

Figure 9. Distance traveled as a function of the *Rate-command* ratio

1. The **terrain assessment** was difficult to perform from single poor quality gray-scaled 2D images. In some areas, the terrain was rough and uneven, making terrain assessment from 2D images (i.e., estimating the slope and height of the obstacles) more difficult.
2. The ***Position-control*** **driving mode** was useful and highly used. In light of the observed results, the safest mode appears to be *Position-control* for complex situations (e.g., in the Arroyo). This mode allowed a clear decoupling of the translation and the rotation (i.e., moving by distance or relative angle). The driver is less likely to commit a driving fault since he can focus on one degree of freedom at the time. A few teams experience driving incidents when sending a long path to the rover, as sending a long path should only be used in safe and open areas. The major weakness of this mode, as implemented, was the difference between the clicked pixel and the true position reached by the rover. This introduces a higher inherent uncertainty to the path to be followed. This driving mode is clearly more resilient than the *Rate-command* mode against the communication constraints because the position control loop is closed onboard as opposed to be closed on the ground with a human in the loop.
3. **Situational awareness** was acceptable and the distance overlays proved to be useful. In complex situations such as the Arroyo traverse, the distance overlays were intensively used and reported to be helpful. The PTZ view is useful for both the driver and the navigator. Most teams have reported that both the driver and the navigator used the PTZ view and that the panoramic view was also improving situational awareness for navigation tasks.
4. The addition of an **onboard localization system** assisted the operators in conducting the mission. The display in the RCS showing the site maps and the rover trajectory proved to be useful and was highly used. Moreover, no team got lost during deployment, even though for some of them the localization system was unreliable. The nature of the site may also explain the success of the team in achieving accurate navigation when the localization system was unavailable. The site contained several unique natural and artificial landmarks providing useful cues that probably helped the navigators confirm the rover location and heading.

5 Comparison with Lunokhod 2

Section 5 presents the results of the main deployment in contrast with the results of the Soviet's mission Luna 21, where the rover Lunokhod 2 explored the surface of the Moon. The information presented in this section about Luna 21 mission were extracted from the Brian Harvey's book [5]. The results presented in Section 4.2.2 seem to be in line with the Luna 21 mission. The operators drove the Lunokhod 2 using degraded imagery coming from 5 cameras, and used hand-controllers to send velocity commands. The concept of operation implemented was similar in some points to the *Rate-command* mode tested during the main deployment.

The average speed reached by Lunokhod 2 was 0.26 m/min, which is about 10 times slower than the average speed reached by the TRT rover. This difference of speed is explained partly by the fact that TRT had higher quality image feeds and the image update was faster (about 3 times faster for TRT). The principal reason explaining the lower speed of Lunokhod 2 is probably the context of the operations. The main deployment was a mission simulation involving no serious consequence resulting from committing a fault. Lunokhod operations were conducted under the highly competitive settings of the Cold War and was a real flight mission with no room for operator mistakes. The operators were extremely prudent and this may explain why the Lunokhod travelled slower than the TRT.

Operating the Lunokhod was also an exhausting task. The operators performed only two continuous hours of operation before they were replaced by a another team. Similar observations were made during the operations of TRT, where most of the operators expressed a high level of fatigue after their three-hour mission.

6 Conclusions and Future Works

The CSA TRT was deployed on several analogue sites in 2013 to perform an intensive field testing campaign. The principal objectives of these deployments were to assess a simple concept of operation in preparation for future missions on the lunar surface. For the main deployment, nine teams composed of CSA employees and industry partners performed as rover operators. A total of 27 hours of operation and a total distance of 2.9 km traveled by the rover were accounted. The mission brought the rover to challenging areas and most of the operators succeeded without committing major driving errors. The level of training provided to the operators was also short (3 hours); one could assume that with more realistic training sessions, including more practice, the operators might have carried out the mission with few or no driving faults. However, some conditions were encountered during the mission where the operators, using the tools provided to them, did not have sufficient information to ensure 100% safe operations. The ConOps tested was simple and did not rely on neither complex vision systems nor complex onboard algorithms.

This project revealed that the tested ConOps could be suitable to support some driving tasks on the Moon, but suffers from the following main limitations: 1) the rover has to move slowly to ensure safe operations and the rover is likely to be stationary most of the time, and 2) the operators are exhausted after three hours of continuous operation. Those conclusions match the lessons learned from the Lunokhod 2 mission, performed under a ConOps similar to the *Rate-command* mode with Lunokhod 2 driven at low speed to carry out safe operations, and operators being exhausted after two hours of operations.

The addition of a fully integrated 3D sensor is the next logical step following this project. Preliminary results using stereo cameras, providing 3D data, showed a clear improvement in situational awareness as it helped resolving ambiguities in 2D imagery. It would be relevant to consistently evaluate if 3D information is improving situation awareness in situations were operators failed during the main deployment reported in this paper.

7 Acknowledgment

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