LUNAR EXPLORATION ANALOGUE DEPLOYMENT (LEAD): OVERVIEW OF THE 2017-2019 ROBOTIC SAMPLE RETURN MISSION SIMULATIONS

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ABSTRACT

In 2017 and 2019 the Canadian Space Agency (CSA) and the European Space Agency (ESA) conducted joint mission simulations in preparation for a potential sample return lunar rover mission. These simulations were conducted to study several mission elements such as: concepts of operation, robotic systems, and to measure driving performance metrics such as achievable average speed. The 2017/2019 simulations cumulated 6.8 km of distance traveled by the rover and 67 hours of on-console operation. In 2019, the operators achieved an overall average speed of 3.4 m/min (0.2 km/h) when they explicitly controlled the rover using several driving modes. This was found to be slower when compared to the rover average speed of 4.4 m/min measured in autonomous navigation .

1 INTRODUCTION

Over the last decade, the Moon has been attracting an extraordinary amount of growing interest from nations around the globe. The Canadian Space Agency is collaborating with its international partners to define concepts for collaborative missions beyond low Earth orbit. In addition to the Lunar Orbital Platform-Gateway, for which the CSA will provide a robotic manipulator, options for lunar surface mobility are also part of CSA's current interest. The CSA's Lunar Analogue Exploration Deployment (LEAD) and the ESA's Human Operations Precursor Experiments (HOPE) projects collaborated to conduct two joint lunar mission simulations. On two occasions, in 2017 and 2019, the CSA's Juno rover was deployed at a rock quarry modified to emulate a lunar landscape. Teams of ESA and CSA operators took turns controlling the rover remotely under a constrained communication link from two control rooms: one at CSA headquarters (Saint-Hubert, Canada) and the other at ESA's ESOC center (Darmstadt, Germany). The mission emulated various segments of ESA's Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) mission [1] such as rover teleoperation, mobility, sample acquisition and storage with subsequent transfer to lander, as well as operations under very low light/dark conditions. This paper is organized as follows. Section 2 outlines previous work conducted by CSA on related topics. Section 3 details the mission simulation architecture, the analogue site and the objectives, followed by Section 4 that presents the deployed testbed and the robotic systems. The results and the principal lessons learned are presented in Section 5.

2 PREVIOUS WORKS

The LEAD mission development was built on previous work reported by CSA in [2]. In this work carried out in 2013, a similar study assessed concepts of operation for rover driving modes in a lunar context. The main difference between 2017/2019 and 2013 rovers in terms of architecture was the limited suites of sensors installed on the 2013 rover, which was not equipped with a 3D Lidar scanner, and the lack of 3D visualization tools available on the operator station. The rest of the architecture was similar. During a two-week deployment, nine teams performed the same three-hour driving mission scenario. The 2013 rover drove a total of 27 hours of operation and traveled 2.9 km. The principal lesson learned from that study was the requirement for a 3D sensor along with appropriate 3D operator station tools. The lessons learned were then fed into the design supporting the LEAD project, under the expectations of improving the operator driving performance.

3 MISSION SIMULATIONS

3.1 Overview

The LEAD project was conducted via the following three sets of mission simulations.

1. The LEAD/HOPE component of the mission focused on having trained operators carry out HERACLES inspired sample return missions described in [1]. Team roles were shared between ESA and CSA. Those simulations took place over five days of operations in October 2017 and four days in June 2019.

2. The LEAD Rover Metrics Gathering Experiment (LRMGE) had six teams in June 2019 operating the rover for about 3.5 hours each along the same predefined itinerary to gather metrics on rover driving performance. In order to compare operator traversal performance against automated driving, the same itinerary was also followed by the rover in autonomous navigation (Autonav) mode.

3. The LEAD Permanently Shadowed Region (PSR) experiment focused on rover driving tasks under dark lighting conditions emulating operations in a PSR. During one night in September 2019, ESA's operators remotely drove the rover on the CSA Analogue Terrain through nine waypoints. The following night, CSA operators not previously exposed to the previous night mission were tasked with running the same scenario. This PSR scenario was later executed in Autonav mode for comparison.

3.2 Analogue Sites

Both LEAD/HOPE and LRMGE were conducted in a rock quarry located within the vicinity of the CSA headquarters. The test site developed at the quarry, which spanned an area of roughly 700 m by 330 m, was shaped to emulate a lunar surface. Fig. 1 shows a part of that site. The PSR mission took place at the CSA Analogue Terrain that is mainly a sandy terrain of 60 m by 120 m located at the CSA's headquarters.

Figure 1: Analogue site developed for LEAD/HOPE

3.3 Simulation Objectives

The main objectives of the LEAD simulations were:

1. Characterize the average rover speed that can realistically be achieved under the 4 available rover control modes, described later;

2. Evaluate the efficiency of an enhanced 3D-centric operator station;

3. Test the rover and manipulator positioning capability over sampling sites and collect a given set of rock and soil samples;

4. Demonstrate the storage of the samples to a sample collection canister and demonstrate its return to a lander mockup;

5. Perform an internationally distributed operations mission simulation.

3.4 Personnel and Operation Team Description

The LEAD/HOPE simulation involved an "in-simulation" team composed of one rover driver, one rover navigator, a mission surface coordinator referred to as "Surface Ops", as well as combined flight director and CAPCOM roles for coordination at both locations. The "in-simulation" team was shadowed by an "out-of-simulation" team of instructors that were acting as liaison between the field team at the deployment site and Surface Ops. The scenario constrained the operations to 6 hours per day for a given team of operators. The operators were either engineers working in robotics or robotics flight mission controllers. The driver's job was to safely drive the rover, while the navigator's main job was to guide the driver toward the mission goals. For the LRMGE, the teams were also composed of a driver and a navigator. The PSR scenario implemented the same operational architecture as the LEAD/HOPE simulation. Prior to attending a formal training course at CSA, all operators were required to watch a detailed software/Apogy webinar which presented how to control the rover via the dedicated control station. ESA ESOC operators received about three days of formal on-console training at CSA prior to the mission. The other operators received about a half-day formal training period.

4 TESTBED AND SYSTEMS

4.1 LEAD Rover

The 2017 and 2019 LEAD simulations were conducted using a CSA Juno rover. Fig. 2 depicts the fully equipped Juno commonly referred as the Teleoperation Robotics Testbed (TRT) or the LEAD Rover in this paper as of 2019 configuration. The LEAD rover was configured to allow two ranges of driving speed, i.e. 0 to 1.8 km/h or 0 to 3.2 km/h (respectively referred in this paper as "low-speed" and "high-speed" ranges). The rover was equipped with several vision systems: three wide-angle drive cameras (i.e. 145° horizontal field-of-view), a science camera featuring pan-tilt-zoom capabilities and providing 360° visibility and panoramic images, two robot manipulator

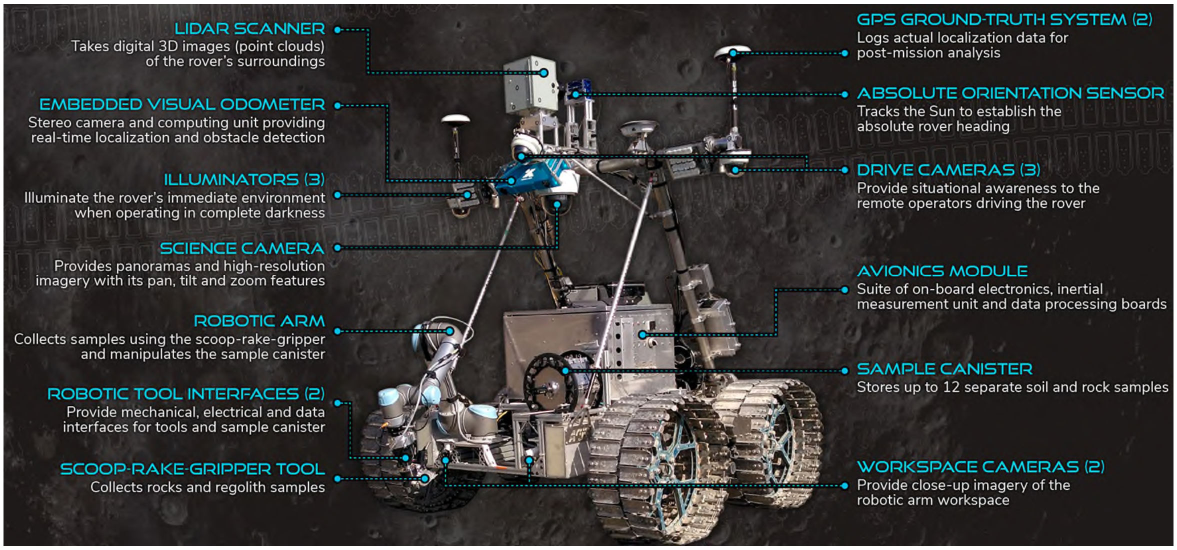

Figure 2: CSA Juno rover as configured for the LEAD 2019 mission simulations

workspace cameras, a stereo camera, and a 360° Lidar scanner featuring a maximum range of about 20 m. Fig. 2 also includes descriptions of the principal robotic components. A set of on-board automated scripts, launched and monitored remotely by the operators, enabled the samples to be acquired, stored and delivered. Details on the sample acquisition, storage and handling technology developed by CSA are available in [3]. The LEAD 2019 improvements over the 2017 campaign included a realistic Guidance, Navigation and Control (GN&C) software suite composed of the following principal systems.

1. The localization system fuses the Inertial Measurement Unit signal with wheel odometry using a dynamic observer to establish rover pose. It should be noted that the absolute heading estimator shown in Fig. 2 was not used during the LEAD campaign.

2. The Driving Hazard Detector (DHD) analyzes stereo images at a rate of 5 Hz to assess the terrain traversability in front of the rover. Upon a DHD obstacle (e.g., rock, hole, cliff, rough terrain) detection, the rover automatically pauses and engages its brakes. Additionally, the rover pauses and engages its brakes if an inclination in excess of 15° is detected.

3. The Autonav system allows autonomous driving to an operator-specified destination that may fall outside of the rover's sensing horizon. It uses a 3D point-cloud acquired by a Lidar representing the terrain in front of the rover to plan collision-free paths to be tracked by the rover's control system. See [4] for further details on this system.

To increase the realism of the deployed GN&C concepts, all main GN&C software components were running on low power processing boards on-board the rover (i.e. Q7 cards from Xiphos Systems Corporation) featuring spaceflight heritage and currently planned to be deployed on the lunar surface in 2021. During the simulations, the operators had access to the following rover control modes:

Teledriving mode: in this mode, the operator has control of the rover's direction using a hand controller which sends body velocity commands (translation and rotation);

Move-by-distance / Turn-by-angle: in this mode, the operator sends a desired position increment (or heading change) to the rover in terms of distance or angle. When the command is received, the rover onboard control system brings the rover to the desired position and/or heading;

Follow-path: in this mode, the operator sends desired paths to the rover by using the 3D visual environment in Apogy control station (detailed in Sec. 4.2). The operator clicks in the 3D view to create a set of waypoints defining the desired path. However, in this mode, the rover can only react when it observes an obstacle by stopping, and is not able to plan a path around it.

Autonav mode: in this mode, the operator sends a single waypoint to indicate desired destination. The destination could be hundreds of meters away from the rover current location. This mode is the less demanding for the operators since all the terrain assessment and planning are handled on-board by the GN&C system. It should be noted that the Autonav mode was not available during the 2017 simulation.

4.2 Remote Control Stations

The planning, control and monitoring of the rover was primarily performed using the Apogy software suite [5] developed in-house at the CSA. The LEAD Apogy station provided the operators with an interface to the rover and its payloads. It allows the operators to send and test commands, monitor telemetry and log the resulting data products. In addition to the CSA Apogy software that was available at CSA and ESA, the ESOC team in Germany accessed the rover telemetry and sent driving commands via their Mission Operations Environment (MOE). The software was primarily used by the team located at ESOC to validate software interoperability from different locations. These operations were performed using a CSA central server and a 3G cell phone communication link with a software-emulated round trip delay of 10 seconds representing an Earth-Gateway-Moon telecommunications path with expected associated communication delay.

5 RESULTS

5.1 LEAD/HOPE

The results presented here were gathered from the mission simulations to address the objectives listed in Section 3.3. Results related to the sample handling objectives are further detailed in [3]. The expression "travel average speed" refers to the ratio of the distance traveled per the duration of a driving task, which includes the moments where the rover was stationary to allow the motion planning by the operators (or the Autonav system). The "travel stationary ratio" refers to the ratio of the time where the rover was stationary versus when it was moving during a driving task. The space available for this publication being limited, the focus of this paper is on the 2019 simulation. The 2017 campaign was defined as a rehearsal conducted in preparation for the 2019 formal simulation. Unless otherwise specified, the results presented in Sect. 5.1 apply to the 2019 LEAD/HOPE campaign.

Fig. 3 depicts an overview of the 2017 and 2019 LEAD/HOPE missions. For comparison, the path followed by the rover during the 2017 mission rehearsal is represented by the dotted black line. The solid colored lines outline the paths followed in 2019 as tracked by the on-board rover localization system for each operation day. The numbers shown in white represent the locations of the nineteen proposed destinations to be reached by the rover in 2019. Some target destinations required the operators to collect a rock or a soil "regolith" sample. The locations where a sample was acquired are labeled in Fig. 3. The mission scenario began with the rover near its lander (location "0" in Fig. 3). During LEAD/HOPE simulation, the operators were free to decide which control modes they wanted to use. It was observed that operators opted to use Teledriving mode only marginally (0.1% of the time), and was used only to recover the rover when stuck in a steep slope on Day 4.

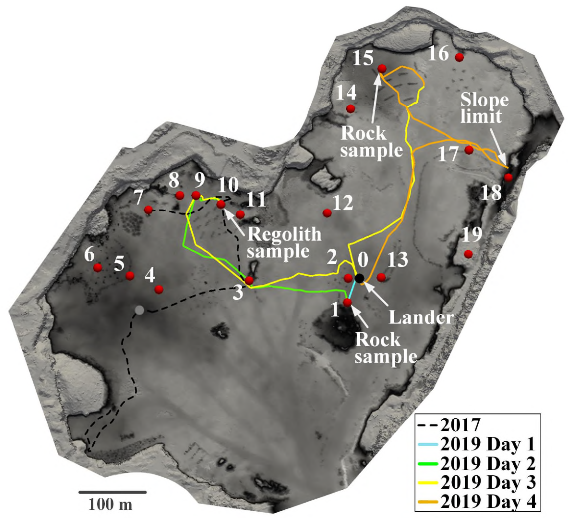

Figure 3: Overview of the 2019 LEAD/HOPE missions as executed

The Move-by-distance/Turn-by-angle mode was clearly the most favourable driving mode. It was used for almost three quarters of the total travel time (74%). Follow-path mode was chosen 17% of the time while Autonav was 9%. It is interesting to note that among the 1585 m traveled during the mission in 2019, the majority (52%) of that distance was traversed using the Follow-path control mode. This makes the latter mode in appearance the most efficient mode, with a travel average speed around 13 m/min, by far the fastest mode. However, the length of the paths used with the Follow-path mode were considered too long to be recognized as realistically safe (and therefore not representative of a spaceflight mission), and as such these commands were excluded from the compiled average speed. Indeed, all Follow-path commands executed by the rover during LEAD/HOPE 2019 were greater than 15 m (54 m on average). At 15 m from the rover, a 22 cm cubic obstacle effectively occupies ~0 pixel in the rover center camera view, and is thus impossible to detect at the start of motion. On top of this, no operator spent the time to thoroughly inspect the entire rover planned route using the pan, tilt and zoom capabilities of the science camera since this would have taken a significant amount of time. As a consequence, the operators were nearly "blind" when they defined the Follow-path commands sent to the rover, relying only on the DHD to prevent a collision. This is what happened on Day 3 in which a collision with a rock was avoided when the DHD system overrode an unsafe command and automatically engaged the brakes. The performance metrics measured during LEAD/HOPE are discussed in Section 5.4.

Four sampling operations have been conducted during the mission simulation. The science target selection phase duration ranged from 5 min to 59 min. On average it took 100 minutes to collect a sample, from the beginning of the rover alignment phase to the end of the sampling operation with the arm stowed. For the four sampling operations carried out, the rover alignment phase was relatively simple since it required, on average, only 16 min and 5 Move-by-distance/Turn-by-angle commands to get the rover aligned with the samples. Despite the limited training received by the operators on the sample handling subsystem, the selection phase of the target sample in Apogy was generally straightforward, except on Day 1, when the first selected rock sample ended up being too small to be collected. This event highlighted the challenge of remotely estimating rock sizes and the need for more exhaustive training and better size assessment tools. On Day 2, the operators mistakenly did not select a "regolith" sample within the allowed arm workspace. As a result, the arm collided with the rover structure but simply paused and did not cause any damage. The robot arm sampling phase took the most time to conduct. That phase required more steps than the other phases. These steps involved sequentially loading and executing several scripts, as well as constant operator monitoring to ensure the scripted maneuvers ran as expected.

The LEAD/HOPE mission ended once the Sample Canister (SaC) was successfully delivered to a lander mockup. To do this, the operators had to first correctly align the rover with the lander. This alignment was completed in 48 min. Fig. 4 shows the rover correctly aligned as seen from the rover's centre camera view. The operators sent a total of 16 Move-by-distance/Turn-by-angle commands to align the red overlay lines shown in Fig. 4 with the alignment features attached on the lander.

Once the rover was correctly aligned, the next step was to transfer the SaC to a dedicated lander's fixture. This was achieved by the robotic arm which grasped a grapple pin on the SaC and then transferred it to the lander. The transfer operation was completed in 31 minutes under nominal operations and thus concluded the 2019 LEAD/HOPE simulation. Fig. 5 shows the transfer of the SaC. Futher details and results on the SaC handling and transfer are available in [3].

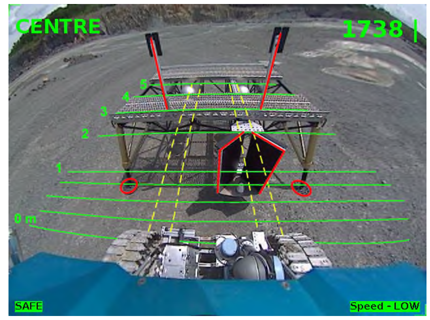

Figure 4: Rover properly aligned with the lander for Sample Container delivery

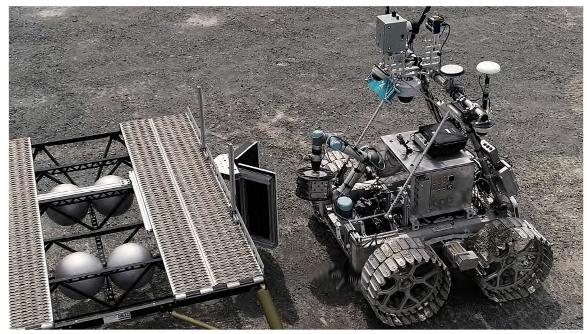

Figure 5: LEAD Rover delivering the SaC

5.2 LRMGE

For the Lunar Rover Metrics Gathering Experiment, the mission objective was to drive the rover from a starting location to a final destination via a set of waypoints which were selected to ensure the rover had to traverse diverse terrain topographies and obstacle densities. This required the operators to use different functions and modes of operation. The control mode was imposed on the operators while traversing between the first five waypoints, and then the choice of mode was left to the operators for the remaining 5 traverse segments. It was not expected that operators were to be able to complete the entire route during their 3.5 hours operations window. The purpose of the LRMGE was to gather metrics regarding the execution of the driving tasks required to conduct a mission such as HERACLES. Fig. 6 shows the LRMGE destinations to reach (from waypoint "a" to "j") along with the path followed by the rover during the run executed by the team that went farthest in to the itinerary.

The rover traveled a cumulative distance of 2965 m throughout the entire LRMGE experiment. Overall, all teams managed to safely drive the rover. The field safety officer did not have to engage the emergency stop on any occasion. However, the DHD system automatically stopped the rover to prevent collisions on four occasions: once in front of a deep hole, twice because of the proximity of a high rock (i.e. above 25 cm), and once because the operators intentionally wanted to drive over a high bush to test if the DHD would react. The details on the operator driving performance metrics are presented in Sec. 5.4.

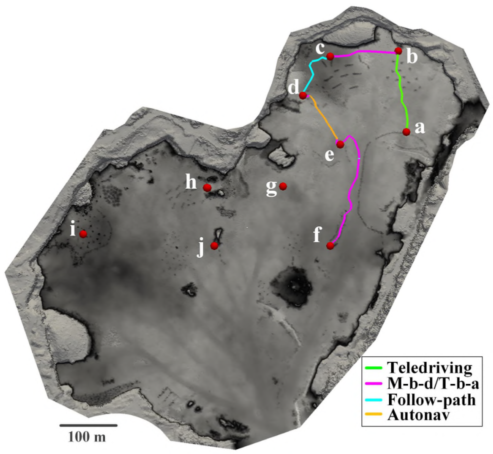

Figure 6: LRMGE itinerary and example of a path executed by a one of the operator teams

In order to compare operator performance to automated driving, the same itinerary (i.e. from location “a” to “f” shown in Fig. 6) was also followed by the rover in autonomous navigation mode. About half of the scenario was executed in low-speed mode and the rest in high-speed. The execution of the traverses in Autonav went well overall. A problem occurred twice when the Lidar scans fed to the Autonav engine were plagued by noisy 3D points, generating artifacts in the scan and making the Autonav’s path-planning unsuccessful. This issue was not a problem with the Autonav system, but rather a Lidar sensing and filtering issue. LEAD/HOPE simulations also encountered this problem. As a consequence, some operators preferred to use other modes of control, limiting the use of Autonav. When the scan artifact problem occurred, the operator aborted the plan and restarted it to prevent the Autonav from entering into its recovery modes that could take several minutes to find a solution. The Autonav system carried out the 597 m traverse required to navigate from location “a” to “f”, demonstrating travel average speeds of 4.3 m/min in low-speed and 4.9 m/min in high-speed mode.

5.3 PSR Simulated Runs

The Permanently Shadowed Region mission scenario was similar to the one developed for the LEAD/HOPE mission for which the operators had to drive the rover to different waypoints. It should be noted that because of logistics constraints, it was not possible to conduct the PSR mission at the same site as LEAD/HOPE mission. Consequently, the CSA Analogue Terrain was used to support the PSR mission. Fig. 7 shows an overview of the PSR mission as executed, in which the rover was operated by two teams (represented by the pink and yellow lines) and by the Autonav system (represented by the green line). The scenario of the mission was to start from location “0” (shown in Fig. 7) and to visit all waypoints (“1” to “9”) and then come back to the starting point “0”.

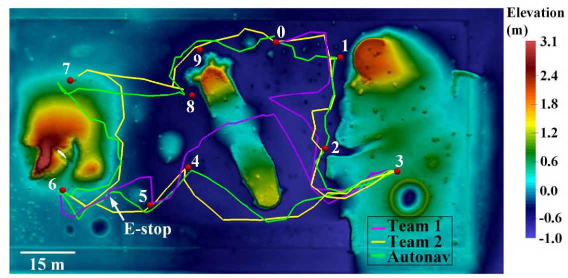

Figure 7: Overview of the PSR mission as executed by the operators and the Autonav

Team 1 forced the field safety officer to engage the emergency stop (E-stop) once the rover back left wheel collided with a 26 cm high rock during a point-turn maneuver. That E-stop event was the sole occurrence of an emergency stop over the entire LEAD 2019 campaign. Fig. 8 shows that rock “hidden” in the rover’s shadow (emphasized by the red circle).

Figure 8: Rock that triggered an E-stop as seen from a field camera (left) and from the rover’s left side camera (right)

Clearly, the operators were not able to see the rock once it entered the rover’s shadow. However, analysis of the rover imagery revealed that the rock was visible to the operators before disappearing in the shadow. Team 1’s journey ended at Waypoint “6” after 215 m of distance traveled. Team 2 started the same PSR mission the night after Team 1. Team 2 was able to complete the entire mission plan within the allocated time. Waypoint “6” was located in the most difficult terrain. In this region, Team 2 (as did Team 1) struggled to find a safe path leading to

Waypoint “6”. This was due to an obstacle composed of three rocks (referred to as the Three-rock-obstacle) 1.6 meters in front of the rover for which Team 2 was not able to determine its traversability solely from camera imagery. The team had concerns that the rover might not have sufficient ground clearance to drive over this obstacle. Fig. 9 shows the Three-rock-obstacle as seen from the rover’s centre and science cameras.

Figure 9: Three-rock-obstacle 1.6 m in front of the rover as seen by the centre (left) and from the science (right) rover cameras

The Three-rock-obstacle highlighted in Fig. 9 cannot easily be assessed in terms of traversability purely from the rover camera imagery since an image does not provide explicit 3D information. The operators took a Lidar scan of the rover’s surroundings to extract a 3D model of it. A simulation in Apogy of the planned motion allowed the team to assess the relative size of the Three-rock-obstacle with a simulated “phantom” rover executing the motion. The rock was deemed traversable and Team 2 decided to drive over it with no resulting issues. The completion of the PSR mission required Team 2 to drive 325 m.

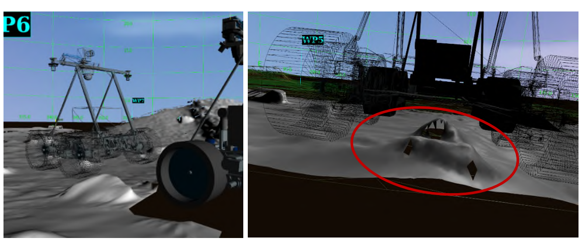

Figure 10: Three-rock-obstacle seen in Apogy view compared with a “phantom” rover (wiremesh)

The PSR scenario was also conducted in Autonav mode. The PSR mission plan was executed once with the rover configured in low-speed mode, and again later in high-speed mode. Fig. 7 shows an overview of the run conducted in Autonav low-speed (green line). The two Autonav runs went successfully overall. However, the Autonav encountered a problem when it tried to leave the region of Waypoint “6” using a different path than the one used to get there. This region was highly challenging and the operator was required to abort the Autonav, manually move the rover a few meters, and then resume the Autonav run to escape this area.

5.4 Summary Results and Discussion

Tab. 1 shows a summary of the results. LEAD/HOPE and LRMGE have been combined together because of the similarity between these two experiments. In the results presentation, the PSR mission remains isolated from the others because the experimental conditions (i.e. test site and lighting conditions) were significantly different. The average downlink bandwidth (i.e. in the telemetry direction) use was substantially different between LEAD/HOPE/LRMGE and PSR missions. This variation is explained by a system modification that was enabled for the PSR mission only. That modification enabled the system to automatically adjust the rover camera rate and avoid, for instance, transmitting images while the rover was stationary. The implementation of the “Autorate” feature resulted in a 76% bandwidth use reduction.

The results presented in Tab. 1 underline that Autonav mode offers faster travel speed than the average speed recorded during the runs where the rover was explicitly driven by operators (i.e., under Teledriving, Move-by-distance/Turn-by-angle and Follow-path modes). This observation was particularly obvious during the PSR mission where Autonav was 119% faster than the operators while using other modes. Interestingly, the operators were 53% slower overall during the PSR operations when compared to operations during daylight. Similarly, the travel stationary ratio was 10% higher during the PSR mission conducted in teleoperation than it was during the LEAD/HOPE/LRMGE missions probably because of the harsher lighting conditions that implied longer command planning processes. The slowest driving mode was the Move-by-distance/Turn-by-angle. However, the latter mode is likely the safest way to drive the rover since the operators only control one degree-of-freedom at the time. This mode has been successful at safely and precisely aligning the rover with respect to the lander for the sample transfer and to position the rover for sampling during LEAD/HOPE. During the PSR mission, the Move-by-distance/Turn-by-angle mode has also been a precise and safe mode to drive the rover in a region of high rock density near Waypoint 6. This mode has been by far the most popular control mode. The operators choose that mode 74% of the time during LEAD/HOPE mission and 100% of the time during the PSR mission. It is worth noting that the operation pace was only marginally driven by the rover maximum speed: the time the operators take to plan and to send commands to the rover dominates the timeline.

Table 1: Results summary for 2019 LEAD/HOPE, LRMGE and PSR missions

	LEAD/HOPE and LRMGE combined	PSR Mission	
		Teleoperation	Autonav
Total distance traveled (m)	4550	540	513
Total operation time (h)[1]	38.9	7.3	3.0
Travel stationary ratio (%)	82	90	79
Overall travel average speed (m/min)	3.4 (Teleops) 4.4 (Autonav)	1.6	3.5
Nb of E-stop	0	1	0
Average downlink bandwidth (kbps)	1150 (estimated)	276 (measured)	N/A

[1] The total operation time represents all time in which operators were on duty performing driving or sampling tasks, or solving occasional off-nominal situations.

5.5 Lessons Learned

The following is a summary of the most relevant lessons learned that emerged from the LEAD project. Those are not listed in any specific order. Additional lessons learned are also reported in the ESA's *HOPE-2 Experiment Report* and the CSA's *LEAD CSA ESA Joint Experiments 2019 Rover Operation Report*.

1. Operator training did not convey the limitations of on-board sensors regarding situational awareness and this led to motion commands that put the rover safety in jeopardy;
2. A 3D sensor such as a Lidar can significantly improve operator situational awareness and make Autonav the fastest mode of operation;
3. Bandwidth usage can be dramatically cut-down by being selective about when imagery is downlinked;
4. On-board robust automatic obstacle detection is paramount for safe operation;
5. The proposed tooling and operation for sample acquisition is effective at collecting samples once adequate operator training is being provided.

6 CONCLUSION

The planned mission simulations for LEAD/HOPE took place in 2017 and 2019 as agreed between ESA and CSA. A summary video is available on the CSA web site [6]. The LRMGE experiment allowed CSA to assess the rover travel speed over different driving modes, operator tools and terrains. CSA and ESA also conducted a mission simulation at night, emulating operations in lunar PSR. The vast majority of the objectives have been met and both CSA and ESA have collected a number of meaningful lessons learned and data to support the development of future lunar flight missions. The realism of the future simulations could be improved with: *1)* more constraints on communication bandwidth; *2)* limitations on rover battery autonomy; *3)* implementation of an engineering support backroom; *4)* analogue site which is more lunar-representative; and *5)* better integration of the science and payload teams into the simulation decision making process.

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