Place Revisiting and Teleoperation for a Sample-Return Mission Control Architecture

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Abstract

We have been developing a navigational framework called Network of Reusable Paths that enables a rover to revisit any previously driven-to location quickly and cheaply. This place-revisiting capability enables the parallel analysis of scientific data from several sites of interest in planetary exploration missions, which allows for a methodical downselection of the locations to determine the best candidate site for costly scientific operations (e.g., sampling). The results from an analogue mission at the Canadian Space Agency's Mars Emulation Terrain in Montréal, Canada are presented in which a 220 metre network is built by teleoperating the rover under a five second communication delay. The rover is operated from a remote backroom consisting of science subteams (each assigned to a site) and a rover operations team.

Figure 1. : **The Juno rover visiting a site of interest during a sample-return analogue mission on the Mars Emulation Terrain in Montréal, Canada.**

1 Introduction

The exploration of extraterrestrial planets is of high value to the scientific community. Mars-sample-return missions, in particular, have been listed as a priority for the next decade by both the Global Exploration Strategy [1] (developed by 14 nations including Canada) and the US Planetary Science Decadal Survey for 2013-2022 [2]. To date, however, planetary rovers have been operated in a *serial* method; locations of interest are visited in sequence and all scientific objectives are completed at each location before moving on to the next. The reasoning behind this approach is that rover driving requires a lot of power and introduces risk to the mission, so it is best to complete all desired operations at a given location before risking movement of the rover.

Operating in a serial manner, however, has some drawbacks. Firstly, rovers often have limited resources for performing certain scientific tasks. For example, a rover may only be able to collect and return a single sample. A serial approach means that the science team must make a decision as to which site will be sampled before having the chance to see every site. Secondly, operating in a serial mode is an inefficient way to use multiple operations teams. Since the rover remains stationary during (possibly lengthy) scientific analysis, the rover operations team can be idle for long periods of time.

In contrast, a *parallel* exploration approach is presented in this paper, the goal of which is to make efficient use of both the exploration robot, and the engineering and science teams on earth. This architecture is largely enabled by an onboard mapping and navigation system that we have been developing called Network of Reusable Paths (NRP) [3]. The algorithm allows the robot to autonomously, accurately, and reliably revisit previously explored sites of interest using only a stereo camera. In this approach, the robot is (constantly) either exploring new terrain via teleoperation, retracing it's own path to previously visited sites autonomously, or carrying out scientific activities at a site of interest. We present results from a sample-return analogue mission conducted at the Canadian Space Agency (CSA) in Montréal, Canada. In this analogue mission, 11 sites of interest on 220-metre-long network of paths are identified and analysed in parallel over the course of 5 days.

2 Background

2.1 Network of Reusable Paths

Rover localization in 3D, unstructured, GPS-denied environments is an unsolved problem in robotics. Often, no *a priori* knowledge of the environment is available, and so the rover must navigate using only its onboard sensors [4]. This gives rise to two localization paradigms: absolute localization where the rover pose is determined in some global reference frame, and relative localization where rover poses are stored as a chain of relative transformations.

Absolute localization methods (e.g., SLAM) use loop closures to bound the uncertainty of the rover pose. General SLAM algorithms, however, can be very computationally expensive (prohibitively so in the case of planetary rovers) and do not scale well. In contrast, relative localization methods (e.g., stereo visual odometry) are computationally inexpensive but usually suffer from unbounded error growth.

NRP is a mapping and localization method that addresses some of the drawbacks of relative methods while still remaining computationally efficient. It is based on the stereo visual odometry (VO) pipeline that is already extensively used on current rover platforms [5] and requires only twice the resources of regular VO. The algorithm works in two stages: *mapping* phases and *revisiting* phases [6].

When mapping, the regular stereo VO pipeline is run to localize the rover. At the same time, the visual landmarks used in the VO pipeline (triangulated SURF features in our case) are stored relative to the rover path to create a simple map. When revisiting, current visual landmarks are compared not only against the previous image (as in regular stereo VO), but also against landmarks

Figure 2. : **A Husky rover revisiting a point on a network of reusable paths. The NRP algorithm is accurate enough to enable the rover to repeat along the path in its own tracks using only a stereo camera.**

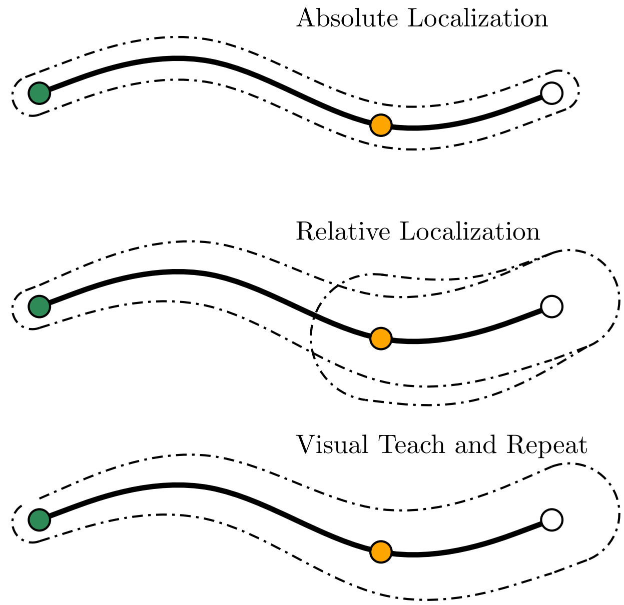

Figure 3. : **Different localization paradigms shown for a sample rover traverse. The rover starts on the left, moves to the far right, and then returns along its path to the middle. Path is shown as a solid line, and the uncertainty envelope is shown as a dashed line. Unlike many relative localization methods, the Visual Teach and Repeat algorithm rolls back its uncertainty when repeating a previously driven path.**

stored in the mapping phase. The algorithm is often accurate enough to enable the rover to autonomously repeat its traverses in its own tracks (see Figure 2). As a result, when repeating along a path, the uncertainty in the rover pose is 'rolled back', as opposed to further increased as in traditional VO [7] (see Figure 3). By alternating between mapping and revisiting, a network of relative paths is built up. No attempt at loop closure is made and so the resulting map is always a tree of paths rooted at the start position.

Being able to accurately repeat traverses along the network is what enables the rover to return to any previously visited location cheaply. Much of the risk of driving rovers is caused by external factors related to the environment (e.g., obstacles, crevices) which need to be detected either using a terrain assessment algorithm or the rover operator. Autonomous terrain assessment algorithms can be computationally expensive and inaccurate, and human-in-the-loop terrain assessment can be slow or difficult to perform. Using the NRP algorithm, however, terrain assessment is required only when building the initial network of paths. After that, the operations teams can be confident in the rover's ability to autonomously repeat its previous traverses without having to redetect unsafe terrain. This often means that the rover can drive more quickly during repeat traverses than during the initial building of the net-

Figure 4. : **The RobuROC6 robot using NRP to autonomously repeating a traverse during a Sudbury lunar-sample-return analogue mission. The algorithm is accurate enough for the rover to drive in its own tracks.**

Figure 5. : **An 'astronaut' alongside the RobuROC6 robot during a lunar-sample-return analogue mission in Mistastin. The 'astronaut' is driving the rover to build a network of paths that can later be repeated autonomously.**

work as well.

2.2 Previous Field Experience

We have previously field tested NRP for parallel science analysis three times. NRP proved useful in two lunar-sample-return analogue missions conducted in Sudbury (rover only) and Mistastin (rover and astronaut) impact structures [8] [9]. NRP revisiting capabilities also benefited a Mars-methane-hunting scenario at the Canadian Space Agency's Mars Emulation Terrain in Montréal, Canada (rover only) [10].

The Sudbury lunar-sample-return analogue mission consisted of a rover driving autonomously to perform the geological investigation of a site. A remote backroom team (science and rover operations) commanded the rover to drive to waypoints of interest in two-hour intervals. The rover used an onboard terrain assessment algorithm to autonomously navigate to the desired waypoint, meanwhile building a network of reusable paths (see Figure 4). The fully autonomous exploration method was slow, and the operations teams quickly realized that repeat traverses were completed much more quickly than new traverses. This led to the natural emergence of a parallel science analysis approach. The science team divided into smaller groups, each responsible for a separate location. This approach maximized the scientific data gathered given the quick command cycles.

The Mistastin lunar-sample-return analogue mission used both a rover and a team of 'astronauts' on site to carry out a geological investigation of a site. The network of paths was built by having the humans manually drive the rover (see Figure 5). This approach was much faster than the fully autonomous mode used in Sudbury but requires an astronaut to be on the surface with the rover, which is extremely costly. Furthermore, real astronauts are limited in time and the distance they can travel from the lander, which limits the network size as well. After the network was driven, the rover was able to autonomously return to any of the outcrops to gather science data for a remote backroom. The 'astronauts' were no longer required

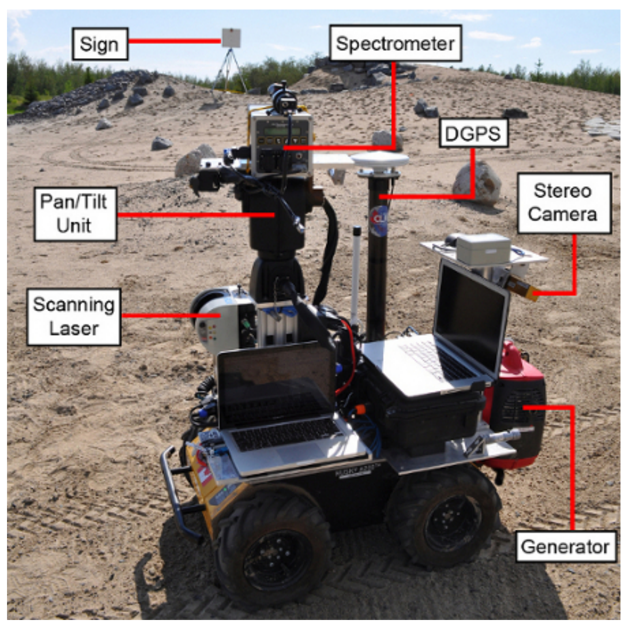

Figure 6. : **A Husky robot on the Mars Emulation Terrain during a Mars-methane-hunting analogue mission. The rover uses a mounted spectrometer to measure the line-of-sight methane concentration between itself and one of four retroreflective signs placed on the terrain.**

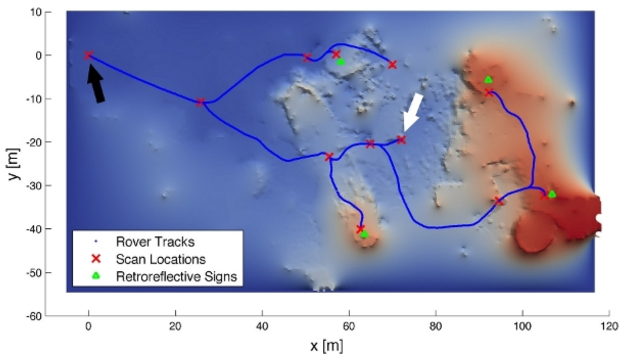

Figure 7. : **A network of reusable paths used during a methane-hunting scenario conducted at the Canadian Space Agency's Mars Emulation Terrain. The paths were established first and then the rover was commanded to many places on the network to gather open-path spectroscopy readings in order to narrow down the methane source location. Black arrow indicates the rover's start location and white arrow indicates the methane source location.**

to supervise the rover and could therefore complete additional scientific tasks in parallel. Finally, the Montréal Mars-methane-hunting analogue mission involved using a rover to locate the source of a methane seep. An artificial methane source was used in the mission to simulate a potential biogenic methane seep on Mars. The methane detection was done by driving a rover-mounted spectrometer to different locations and pointing it at four retroreflective signs, then measuring the absorption of the beam in the return signal to give the methane concentration along the line of sight to the sign (see Figure 6).

The scenario was conducted in two stages. First, the rover was manually driven throughout the test site to build a network of reusable paths and to deploy the four retroreflective signs (see Figure 7). The process was done manually to accelerate this stage of the experiment since it was not the focus of the mission. Second, a remote backroom team would command the rover to repeat to locations on the network to gather methane concentration measurements. These measurements could be unreliable due to unmodelled effects (e.g., wind) and so the science team would often need to return to a location and perform more measurements. The resulting measurements could be hard to interpret, and so a parallel method of exploration was particularly beneficial here; the science team could interpret the current results while at the same time commanding the rover to gather more measurements. The concept seemed to be successful overall, but further work is required in order to be able to properly interpret the methane concentration results to reliably find a methane seep.

3 Methodology

The proposed mission architecture takes advantage of the place-revisiting capabilities of NRP to enable a parallel approach to scientific analysis in a sample-return scenario. The method improves on previous work in two ways: 1) the rover is remotely teleoperated, thus benefitting from the speed of human driving without requiring one on site, and 2) the backroom science team is subdivided from the beginning with a parallel approach in mind.

The robot's time is divided into four separate activities: exploration by teleoperation, site revisiting using NRP autonomy, onsite scientific activities, and a waiting state. In order to minimize the robot downtime, the earth-bound operations team is divided into three groups: 1) the rover operations team, 2) the frontroom science

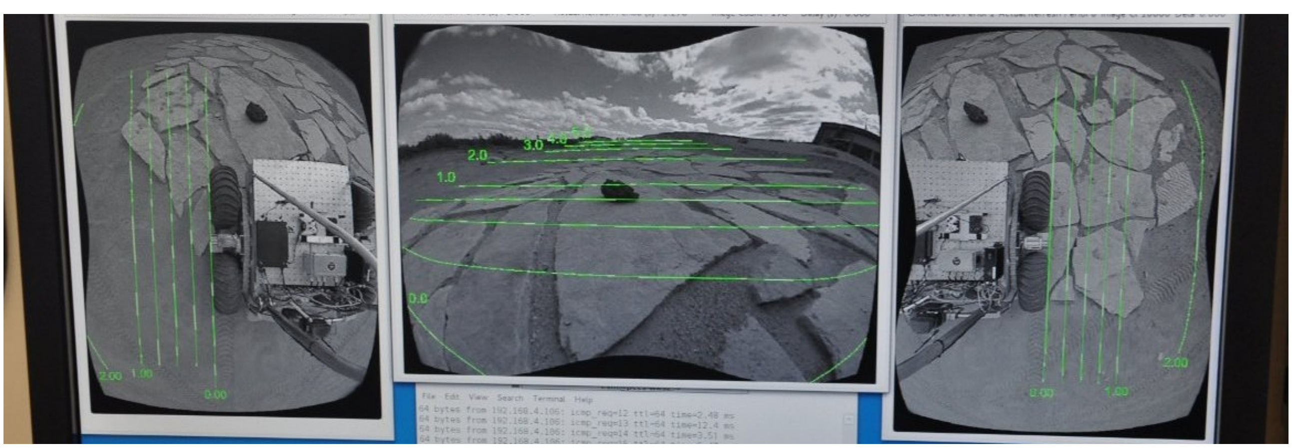

Figure 8. : **The interface used to teleoperate the rover. One forward-facing camera and two side-mounted cameras are used for navigation. Distance overlays are used to help the operator gauge distance from the rover since no range data is available.**

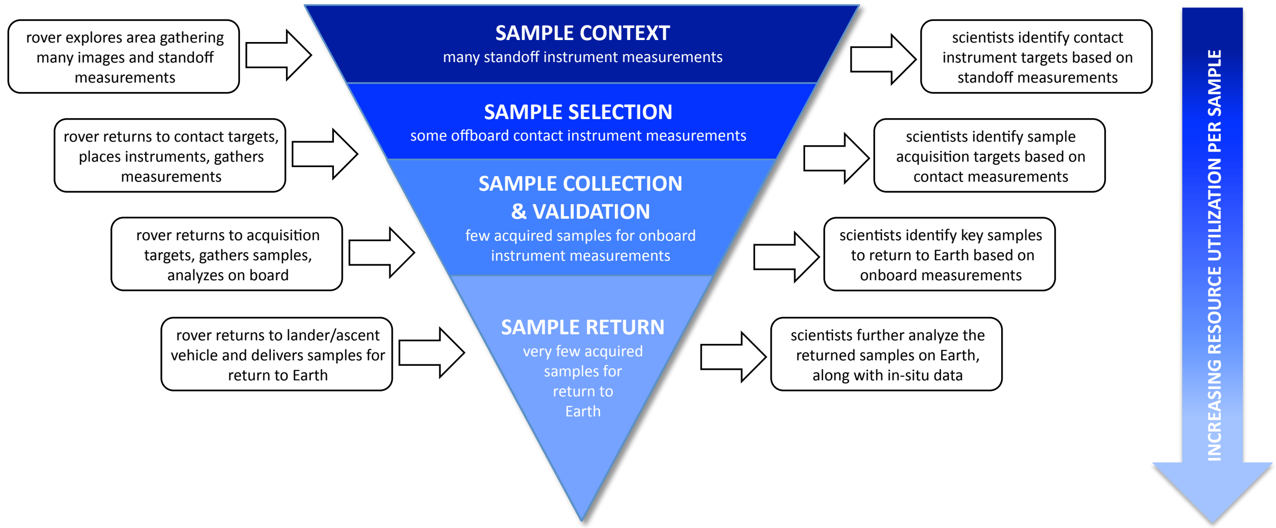

Figure 9. : **The downselection process for scientific sites of interest. Cheap scientific operations are performed at many sites. A subset of these sites are chosen for more in-depth (and more costly) scientific procedures. The process is repeated until the number of remaining sites matches the resources available for the most limited scientific operations (e.g., sampling).**

team (FRST), and 3) the backroom science team (BRST).

3.1 Exploration

During this phase, the front-room science team and rover operations team cooperate to navigate the rover to new sites of interest. The rover is driven via teleoperation, which benefits from human driving capabilities without requiring a human on-site. During exploration, the NRP algorithm accurately records the path of the robot in order to enable future place revisiting. It is the rover team's responsibility to safely plan paths, identify obstacles, and drive the rover to the desired location. During the traverse, the FRST is responsible for indentifying additional sites of interest, which may present themselves at any time during exploration.

The operator uses three fish-eyed cameras to navigate; one pointed forward on the rover and two side-mounted cameras looking down at the rover wheels (see Figure 8). Distance markers are overlayed on the image to help the operator gauge the distance to obstacles and the clearance on the side of the rover. Due to delays in the communication, teleoperation of the rover often proceeds in a stop-and-go fashion, and is generally slower than autonomous repeat traverses using NRP.

3.2 Scientific Analysis

Upon reaching the target site, the rover performs a cursory gathering of scientific data using non-contact instruments (e.g., cameras). The FRST forwards all scientific data to the BRST for detailed analysis. The process is repeated several times, increasing the total number of sites being analysed in parallel. At any point during exploration, the BRST may request that additional data be gathered at a previous site. Using NRP, the rover quickly and accurately returns to the site in order to gather more in-depth – and costly – data (e.g., X-ray spectrometer, RAMAN spectrometer).

The exploration and repeating modes are repeated several times, with the exploration modes discovering new sites, and the BRST removing sites that prove uninterest-

Figure 10. : **The Mars Emulation Terrain at the Canadian Space Agency in Montréal, Canada. The artifical terrain spans 120×60 metres and contains many structures that introduce elevation changes. Scientifically significant rocks were hidden throughout the terrain for the sample-return analogue mission. Start location of the analogue mission marked with a green dot.**

ing. This allows for a methodical downselection of the sites of interest to permit the most efficient use of the limited rover resources. Eventually, the best candidate is chosen for sampling from all of the sites visited (see Figure 9).

4 Analogue Mission

The proposed mission architecture was tested in a sample-return analogue mission on the Canadian Space Agency's (CSA) Mars Emulation Terrain (MET) located in Montréal, Canada. The MET is an artifically created environment that emulates the terrain a rover might encounter on Mars (see Figure 10). The surface is composed of a mixture of sand and rocks of various sizes. Several structures throughout the terrain create elevation changes and block sightlines between different areas. The MET measures 120×60 metres.

Scientifically interesting rocks (see Figure 11) were hidden throughout the terrain to simulate sites of interest and the objective of the analogue mission was to locate and study these rocks. As described in Section 3, the operations team was split into the rover operations team, and the two science teams (FRST and BRST). The backroom team had no *a priori* knowledge of the rocks or their locations during the mission. The start location – and first site of interest – of the rover can be seen in Figure 10.

5 Results and Discussion

Science instrumentation was operated by a separate science field team who otherwise did not interfere with the rover (see Figure 14). No communication was possible between the backroom and field teams except to relay commands for the operation of equipment, and to transfer

Figure 11. : **An example of a scientifically significant rock that was placed on the MET during the analogue mission. A coin is present for scale.**

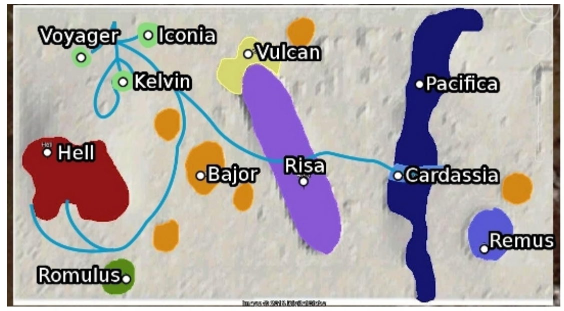

Figure 12. : **The Mars Emulation Terrain with sites of interest labelled. The network of paths driven by the robot is approximately 220 metres in length and shown in blue. The total distance travelled by the rover is much higher as it repeated sections of the network many times. The science team commanded the rover to visit 8 of the 11 sites.**

the resulting data. This was done because autonomous operation of the science instruments was not the focus of this experiment. Each instrument had a time penalty that the backroom had to adhere to in order to simulate the tradeoff between performing science and continuing to the next site. Each instrument also had a minimum and maximum operating range in terms of distance from the rover, again to simulate real conditions [11].

A Juno rover was used as the robot platform for the NRP algorithm (see Figure 1). The Juno rover is extremely capable and can safely drive over many of the obstacles on the MET. Nonetheless, a goal of the mission was to minimize risk to the rover by avoiding all obstacles. As detailed in Section 3, the rover platform was equiped with 3 fish-eyed cameras for teleoperation and a stereo camera for NRP [12]. The robot also included a pan-tilt camera with zoom capabilities for the backroom science team. A five second communication delay was added between the rover and the driver to simulate planetary teleoperation conditions.

The science team was able to successfully command the rover to visit 8 locations of interest. The locations were analysed in parallel to determine which site would be sampled. Throughout the analogue mission, the total network length was 220 metres, but the total driving distance was higher than that due to repeat traverses along the network. The network, along with the labelled sites of interest can be seen in Figure 12.

Teleoperation proved to be an effective method for building the network of reusable paths in a safe and quick way without requiring direct line of sight to the rover. The distance overlays in the navigation camera images were useful for mitigating the effects of the communications delays because they allowed the operator to time the rover

Figure 13. : **The Juno rover being teleoperated to 'Cardasia' under a communications delay. The path to the site leaves very little clearance on either side of the rover, but the side-mounted cameras (with distance overlays) allowed the rover to be driven safely through the hallway.**

traverses according to the approximate distance to nearby obstacles. Especially helpful were the side-mounted cameras, which showed the clearance to the sides of the rover. For example, when approaching the 'Cardassia' location, the Juno rover was required to navigate a hallway-like structure with only 10 centimetres of clearance on either side of the rover (see Figure 13). Even under the large teleoperation delay, the operator was able to slowly but safely navigate to the top almost exclusively using the side-mounted cameras. The benefits of the NRP algorithm were clearly visible here, as the rover autonomously followed its path back through the hallway at a much faster speed than the human operator could achieve.

While teleoperating the rover to build a network of paths was quicker and safer than previous NRP implementations using autonomous driving, it was still much slower than having a human manually drive the rover while next to it. There were several factors that contributed to the slow rover speed during teleoperation. One such factor was the communication delay that forced the operator to drive in a stop-and-go fashion, where the rover was driven for a short amount of time, and then stopped to allow the camera feed to update. This could potentially be mitigated using a predictive display which would allow the operator to drive without current camera feeds in certain relatively safe situations. An onboard terrain assessment algorithm could also be used to aide the operator, allowing them to drive the rover with more confidence because the terrain assessment could provide a safety blanket to prevent rover harm.

The teleoperation method also suffers from the fact that constant, relatively high-bandwidth communication is required with the rover while driving. If the communication link is not good enough, then teleoperation can become impossible. This was evidenced as the rover was driven to the site 'Hell'; the WiFi coverage on the far side of the MET can be sporadic due to occlusion from the nearby terrain features. The operator was able to drive the rover to the site, but the intermittent communication made the process very slow. Using NRP, however, the backroom was able to send a command to return to the base of the network, and once the command had successfully been received by the rover, it was able to autonomously drive through the poor communication area at full speed.

6 Conclusions and Future Work

The place-revisiting capabilities of NRP enable the parallel analysis of scientific data during planetary exploration missions. NRP extends the stereo VO pipeline already present on current rover platforms, and enables the rover to revisit any previously driven-to location at only a small increased computational cost (about twice the resources required for stereo VO). Delayed teleoperation to build the network of paths is a useful method that bridges the gap between fully autonomous exploration and direct human control.

Results from several analogue missions validate the NRP place revisiting for parallel analysis concept as a useful method for exploration missions. Future work will focus on dealing with issues pertaining to using our NRP al-

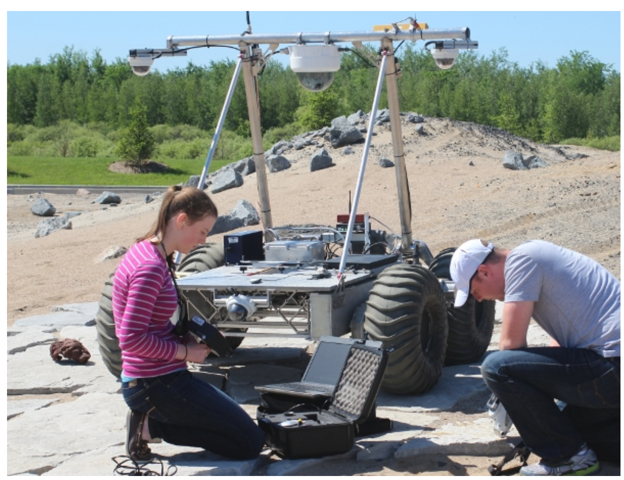

Figure 14. : **The science field team operating the scientific instrumentation during the analogue mission as per the commands issued by the backroom science team. Science data was then relayed back to the backroom team for analysis.**

gorithm in long-term autonomous operations, where both rover and environmental variables may change over time. This future work will include things such as path repair, continuous obstacle detection, and efficient, scalable loop closure.

7 Acknowledgments

The authors would like to acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for their funding of the project, the Centre for Planetary Science and Exploration (CPSX) at Western University for leading the investigation, and the Canadian Space Agency (CSA) for lending us their rover platform and hosting the analogue mission.

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