Place Revisiting for Planetary Rovers: An Enabling Technology and Field Testing of Three Mission Concepts

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***Abstract*— Planetary rovers to date have been operated mainly in a *serial* mode; they are driven from one place to the next, away from the lander, and seldom return to previously visited places. We have been developing a visual navigation technique, called *network of reusable paths* (NRP), that can be thought of as a low-computational-cost version of simultaneous localization and mapping coupled to a path-tracking controller. The result is that a rover can be returned accurately to any place it has previously visited using only visual feedback; this enables science to be gathered from multiple sites in *parallel*. We will describe how NRP works, and present field test results of two mission concepts where we have made use of this technology: a lunar-sample-return scenario and a Mars-methane-hunting scenario.**

I. EXTENDED ABSTRACT

At the time of writing, NASA's Spirit, Opportunity, and Curiosity rovers have driven a combined 44+ kilometres on the surface of Mars, visiting many sites of scientific interest along the way. Their exploration strategies have been *serial* in the sense that scientific objectives are completed at one site before departing for the next. The coming decades will see more advanced missions to both Mars and the Moon. For example, the return of samples is highly desirable from both targets and could benefit from the ability to investigate multiple candidate sampling sites in parallel, in order to methodically downselect the specimens to return. To enable such a parallel investigation, rovers need the ability to accurately *revisit places*.

We have been developing one technology that could enable place revisiting that we call *network of reusable paths* (NRP). NRP leverages the stereo visual odometry (VO) pipeline already standard on current rovers [1], requiring about double the computational resources of VO to enable place revisiting [2]. In essence, the localization/mapping part of NRP runs a stereo VO pipeline with two key differences. First, when establishing new paths, the visual landmarks used to compute motion (triangulated SURF features in our case) are stored relative to the robot's path, creating a simple map. Second, when repeating a path we match the current image not only to the previous image, but also to the path-based map (see Figure 2). NRP also has a planning component based on a rapidly-expanding random tree (RRT), which allows the robot to use the existing paths it has established, but also to branch off into new terrain when necessary to reach a goal. At the moment, NRP makes no attempt to do loop closure and therefore the network is always a tree of paths rooted at the 'lander'. Figure 1 shows an example of a network of paths during one experiment.

Fig. 1. Rover adding to a network of reusable paths on the Canadian Space Agency's Mars Emulation Terrain; once created, it can return accurately to any previously visited place using only visual feedback.

We have field tested NRP in three mission concepts. We found NRP to be a useful capability in two lunar-sample-return scenarios carried out at the Sudbury (robot only) and Mistastin (robot and astronauts) impact structures [3]. We also showed how NRP could be used to conduct a Mars-methane-hunting scenario at the Canadian Space Agency's Mars Emulation Terrain [4].

In the Sudbury lunar-sample-return scenario, a rover was used to carry out a geological investigation of a site. A remote backroom team (scientists and engineers) commanded the rover every two hours (for two weeks) by issuing goal locations. The rover drove autonomously to these goal locations using the NRP framework. The backroom team quickly discovered that if they commanded the robot to revisit a place, it could get there fairly quickly, compared to driving into new terrain where more caution was required. The parallel site investigation concept naturally emerged at

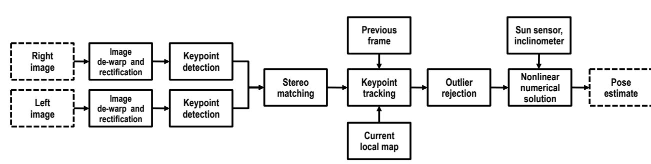

Fig. 2. Modified stereo visual odometry pipeline used in *network of reusable paths*. When repeating a route, we match the current image to the previous image to compute motion, but also to a local map of features stored relative to the path; this allows the robot to compute where it is relative to the path and steer back onto it.

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this point; the science team broke into a small number of groups, each focussed on one site of interest. As the data from one site were being analyzed, the rover was commanded to another site to gather new data. This yielded the most science data given the rapid command cycle schedule.

In the Mistastin lunar-sample-return scenario, a combination of human 'astronauts' and a rover was used to carry out a geological investigation of a site. The astronauts were allowed to use a joystick to pilot the robot, or a backroom team could command the robot remotely. In this case, the most efficient paradigm was to have the astronauts literally teach the robot paths from the 'habitat' to interesting outcrops. The robot could then linger at an outcrop and return home on its own while the astronauts moved on to other sites of interest. The robot could also follow up by easily revisiting outcrops without the astronaut in order to conduct additional measurements.

Finally, in the Mars-methane-hunting scenario, a rover was used to pinpoint a methane source. We used an artificial methane source in our experiment to emulate a potential biogenic methane seep on Mars. To seek the source, a rover-mounted spectrometer was driven to different locations and pointed at four retroreflective signs; the concentration of methane along the line to the sign was measured by bouncing a laser tuned to a frequency absorbed by methane off the signs (see Figure 3). There were two phases to the mission. First, the rover was manually driven throughout the site to build a network of reusable paths (see Figure 4) and to deploy the four signs; we manually drove the robot and deployed the signs to accelerate the field test as this was not the main focus of our experiment. Second, a remote backroom team commanded the rover to revisit places on the network of reusable paths in order to gather methane concentration readings (using the retroreflective signs). Note, the science was 'in the loop' here since previous readings guided where

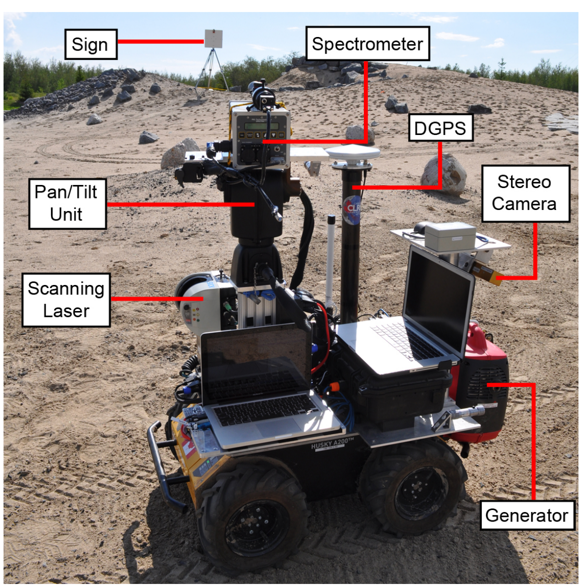

Fig. 3. Rover with science and engineering payloads mounted. System shown pointing spectrometer at a retroreflective sign to measure the gas concentration along the line of sight between the spectrometer and sign.

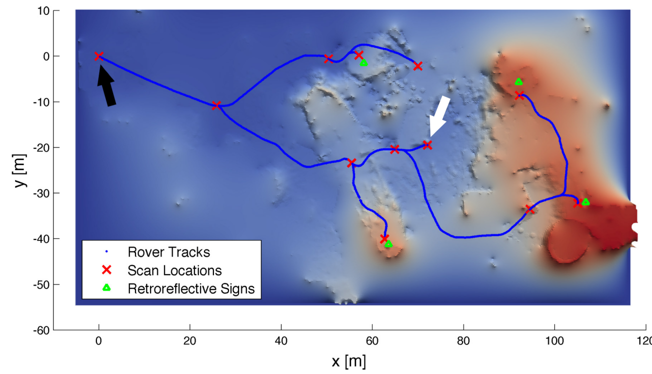

Fig. 4. A network of reusable paths used during a methane-hunting scenario conducted at the Canadian Space Agency's Mars Emulation Terrain. The paths were established first and then the rover was commanded to many places on the network to gather open-path spectroscopy readings in order to narrow down the methane source location. Black arrow indicates the rover's start location and white arrow is the methane source location.

to acquire the next ones. Revisiting places became important for the science team in this concept since some methane readings could be misleading due to unpredictable factors such as wind. The concept seemed to be a viable way to pinpoint a biogas source, but further work is needed to be able to properly interpret the methane readings.

In summary, we believe the network of reusable paths visual navigation framework is a promising concept to allow future planetary rovers to be able to easily revisit places. This capability opens up a variety of new mission concepts and the computational requirements are about double what the standard stereo visual odometry pipeline requires. Our future work will investigate improving the robustness of the technique to disturbances (such as lighting change) and planning for loop closures (in order to repair broken paths and find shortcuts in the network).

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