PLANETARY SURFACE EXPLORATION USING A NETWORK OF REUSABLE PATHS.

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Robotic exploration missions to the Moon or Mars: The Mars Exploration Rovers have driven a combined 40 kilometres, visiting many sites of scientific interest along the way. The exploration strategy was serial in the sense that scientific objectives were completed at one site before departing for the next. The coming decades will see sample return missions to both Mars and the Moon. Here, we advocate for a planetary exploration strategy that allows sites of interest to be studied in parallel, rather than in series. We believe this better supports the overarching aims of sample return missions, as a methodical down-selection process may be employed to identify the key specimens for return to Earth. We present the novel concept of a *network of reusable paths* (NRP) to enable a rover to revisit places of scientific interest and thus to study sites in parallel. Our approach was field tested through mock lunar sample-return mission scenarios conducted in the Sudbury impact crater in Canada [1].

A network of reusable paths: *Teach-and-repeat* systems [2,3,4] allow robots to drive arbitrarily long distances without the use of GPS along previously-established routes. In all these systems, a chain of small maps is attached along the robot's path during a teaching phase; to repeat the route, the robot simply localizes against each small map in sequence as it drives. At any time the robot can return to a previous point on the path. Particularly relevent to lunar exploration is teach and repeat using appearance-based lidar [3]. This system uses an active sensor and is able to overcome lighting issues, allowing operation in conditions ranging from full sunlight to total darkness.

A network of reusable paths, first proposed by Stenning and Barfoot [5], is an extension of teach-and-repeat systems. Instead of a simple chain of local maps, there is an arbitrary network of local maps.

Consider the example network in Figure 2. Here, there are three sites of interest that are being investigated in parallel. While operators on Earth discuss a decision on where to sample at site A, they can send the robot to site B and then C to collect imagery before returning to site A. Then, while the robot is sampling at site A the mission team can use the data from Site B and C to select another potential sampling site. The rover does not need to loiter at a particular site of interest until all the work there is done. It is able to leave and return.

Figure 1: Robot configurations used in the mock mission scenarios in the Sudbury impact crater in Canada. Week one on the left, and week two on the right.

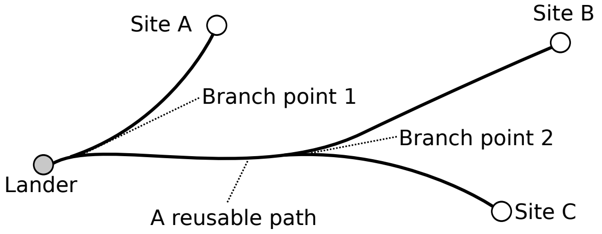

Figure 2: A tree network of reusable paths. A robot can return to any point on the network and can grow the network into new areas. To go from site B to C, the rover reuses the network through branch point 2.

Many variations on this idea are possible, and in the above the benefit is that NRP provides mission operators with the flexibility to delay sampling decisions pending a more thorough investigation of the data already on Earth. This can dramatically improve the efficiency of the system. In practice we found it to be as though there are multiple rovers with offset command cycles.

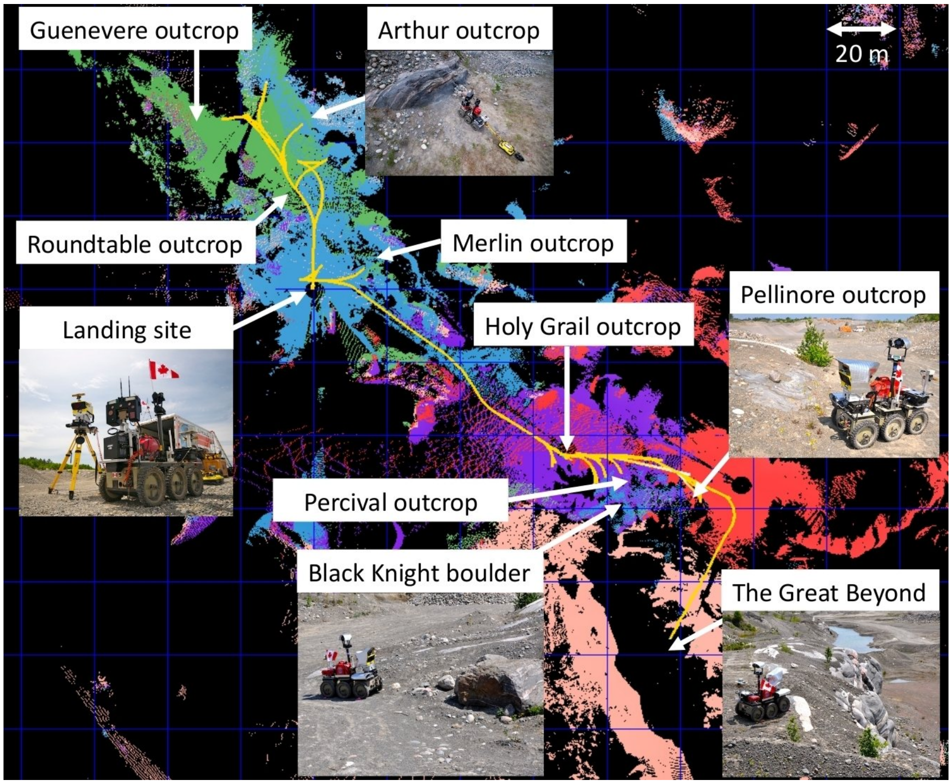

Figure 3: Sudbury robotic exploration scenario. The network of reusable paths is shown as a set of yellow lines. The different coloured patches are unique lidar scans, used to plan rover paths. Outcrop names are provided.

Field trials of purely robotic sample return: The Sudbury field trials used two different robot configurations, shown in Figure 1. Left to right are the configurations used in the first week and second week.

Figure 3 gives an overview of the mock mission from week two. The background is a screen capture of the view from the rover operation station and the photos identify some of the sites that were investigated. Multiple long-range lidar scans are displayed in different colours. The operator would select points shared between scans to merge all the point clouds into a model of the environment. The network of reusable paths is shown in yellow. This network was extended from the network created in the first week. To add to the network the operator defined waypoints relative to any of the point clouds and the robot would autonomously seek those waypoints, detecting and avoiding obstacles using the onboard terrain assessment and NRP path-planning capabilities.

In the first week, 24 command cycles were carried out creating a 0.23 km network while driving a total of 1.0 km. The second week had 19 command cycles, a 0.44 km network and 2.92 km of total driving. The collected samples were returned to the lander for analysis and potential return to Earth.

A network of paths offers a game changing concept for planetary exploration using a mobile robot. NRP has many benefits in the context of robust autonomous navigation [5]. It also allows mission-level improvements by allowing parallel exploration of multiple scientific targets and naturally including sample return. During these analogue missions, this capability enabled an order of magnitude more sites to be visited. Such a capability would be extremely useful for short duration sample return missions on the Moon and Mars.

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