

AUTONOMOUS LONG-RANGE ROVER NAVIGATION – EXPERIMENTAL RESULTS

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ABSTRACT

The success of NASA's Mars Exploration Rovers has demonstrated the important benefits that mobility adds to planetary exploration. With ExoMars and the Mars Science Laboratory missions, mobility will play an ever-increasing role. Very soon, mission requirements will impose that planetary exploration rovers drive over-the-horizon in a single command cycle. This will require an evolution of the methods and technologies currently used.

The Canadian Space Agency (CSA) has been conducting research in ground control and in autonomous robotics for several years already. One of the target applications is planetary exploration using mobile platforms. The emphasis of our research program is on reactive on-board autonomy software and long-range rover navigation.

This paper provides experimental results obtained during the summer 2006 test campaign for several of the key technologies developed under our research program. In particular, the paper describes results in the area of terrain modelling, path planning, rover motion control, and rover localisation. Statistical analyses have been performed on test results, where relevant, to provide an indication of success ratios and performance.

INTRODUCTION

Over the past three years, the Mars Exploration Rovers (MERs) "Spirit" and "Opportunity" have demonstrated the important benefits that mobility adds to landed planetary exploration missions. So far, both rovers have made astounding scientific discoveries and travelled several kilometres, often traversing distances over 100 metres per day [1]. They have demonstrated beyond doubt the necessity and feasibility of semi-autonomous rovers for conducting scientific exploration on other planets.

The operations concept for the planning and execution of traverses for the MER has generally relied on teams of scientists to select target destinations, and rover operators to select a set of via-points to successfully reach this destination. Both "Spirit" and "Opportunity" had the ability to detect and avoid obstacles, picking a path that would take them along a safe trajectory. On occasion, the rovers have had to travel to locations that were at the fringe of the horizon of their sensors or even slightly beyond.

The next rover missions to Mars are the "Mars Science Laboratory" (MSL) [2] and ESA's ExoMars [3]. Both of these missions have set target traverse distances on the order of one kilometre per day. Both the MSL and ExoMars rovers are therefore expected to drive regularly a significant distance beyond the horizon of their environment sensors. Earth-based operators will therefore not know a-priori the detailed geometry of the environment and will thus not be able to select via points for the rovers throughout their traverses. Path and trajectory planning will have to be conducted on-board, which is an evolution from the autonomy model of the MERs.

One of the key technologies that will be required is the ability to sense and model the 3D environment in which the rover has to navigate. For long-range navigation, the ability to localize the rover through the registration of sensor data with the model of the 3D terrain is also required. To address these issues, the Canadian Space Agency is developing a suite of technologies for long-range rover navigation. For the purposes of this paper, "long-range" is defined as a traverse that takes the rover beyond the horizon of the rover's environment sensors.

The typical operational scenario used for our experimentation is based on the following assumptions. The rover has rough *a-priori* knowledge of its surroundings in the form of a low-resolution terrain map. The interaction between the rover and the Earth-based operator is limited to a single command specifying a target destination in absolute coordinates. The rover must first observe its environment to localise itself accurately. It then plans a rough path in the coarse terrain model that will take it from its current estimated position to the target destination. After obtaining this rough path, the rover iteratively takes local scans of its surroundings and navigates segments of the planned path. The local scans are used for three purposes: planning a local path to avoid known obstacles, refining the localisation knowledge throughout the trajectory and constructing an atlas of detailed terrain maps.

This paper presents the key components that have been developed in our laboratory to address some critical issues in rover navigation. The latest experimental results that have been obtained are also presented. The first section presents the terrain modelling algorithms and experimental results obtained on the CSA's Mars emulation terrain. The second section presents a statistical analysis of results from path planning and rover motion control experiments. The third section provides an overview of the localisation scheme along with qualitative experimental results. Finally, anecdotal results for the integrated rover navigation experiments are provided in the last section.

TERRAIN MODELLING

The first step in the navigation process is the sensing and modeling of the terrain through which the rover will navigate. The terrain sensor used on the CSA experimental test-bed is a commercial Light Detection And Ranging (LIDAR) sensor: an ILRIS-3D sensor from Optech. The main advantage of the LIDAR is that it directly provides a 2.5 D point cloud giving the x-y-z coordinates of the terrain in its field of view. The sensor has a range of over 1 kilometre but the data is trimmed down to approximately 30 metres. Some of the specific challenges that must be addressed by the terrain modelling software are the high volume of data (each LIDAR scan has about 500K 3D points) and the highly non-uniform density of the scans due to the fact that the sensor is mounted at a grazing angle. Indeed, to increase the challenges associated with over-the-horizon navigation, the sensor is mounted directly on top of the rover (approximately 50 cm off the ground). This has the effect of shortening the horizon and introducing severe occlusions in the presence of obstacles; see Figure 1.

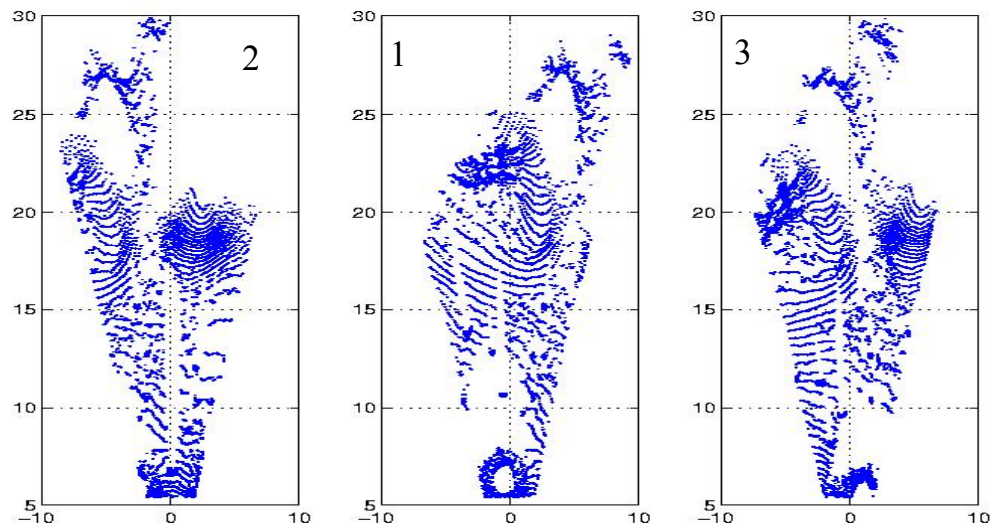


Figure 1 - Typical Terrain Scans taken from LIDAR sensor mounted on robot. Notice non-uniform point cloud density and occlusions.

Since a point cloud is not an appropriate structure to plan navigation, a different representation has to be chosen. One of the requirements of the selected representation is that it must be compatible with navigation algorithms and that it must preserve the scientific data contained in the terrain topography. In addition, the resulting model must be compact in terms of memory usage since the model must reside on-board the rover.

To fulfil these requirements, the irregular triangular-mesh terrain representation was chosen. One of the main advantages of the irregular triangular-mesh over the classical digital elevation maps (DEM) is that it inherently

supports variable resolution. It is therefore possible to decimate the data set, modelling details of uneven areas with high precision while simplifying flat areas to just a few triangles. This minimises the overall memory requirements for a given terrain. The irregular triangular-mesh (ITM) representation also has advantages compared to other variable resolution representations such as quad-trees or other traversability maps, which remove all science content from the topographical data. In addition, both DEM and quad-trees are 2.5D representations. Therefore, they do not support concave geological structures like overhangs and caverns, which pose no problem to the irregular triangular mesh. The implementation of the terrain modelling using triangular mesh is done using the Visualisation Toolkit [4].

As mentioned earlier, an important step is the decimation of the dense point cloud. The decimation algorithm was run repeatedly over the rich data sets obtained in the CSA's Mars emulation terrain. The scans were taken using the ILRIS LIDAR in the same configuration that will be used for the navigation experiments. The terrain is representative of what a rover would encounter in several locations on the surface of Mars.

Table 1 shows the results of the decimation algorithm applied to twelve LIDAR scans. The decimation ratio is the ratio of the number of points removed to the number of points in the original point cloud. The average error is calculated as the numeric average of the distance between every point in the original point cloud and the decimated surface approximated by the irregular triangular mesh. As can be seen, a 70% data reduction ratio resulted in average errors of only 10mm. A data reduction ratio of 90% resulted in average errors on the order of 40mm, which is still acceptable for rover traverse planning.

Table 1 - Properties of Decimated Terrain Scans

	Original Scans	Target Decimation Ratio	
		70%	90%
Average Number of Points	24410	7352	3059
Average Effective Decimation Ratio	N/A	69.9%	86.5%
Average Error (mm)	N/A	10.1	42.9

Figure 2 and Figure 3 below show irregular triangular mesh representations of a typical LIDAR scan before and after decimation. Figure 4 shows the decimated point cloud overlaid on top of the original data set. It shows that the decimation algorithm has reduced the amount of superfluous data and kept the points that are essential to identify features and obstacles in the environment.

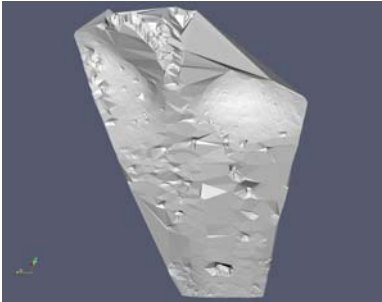


Figure 2 - Original Terrain Model

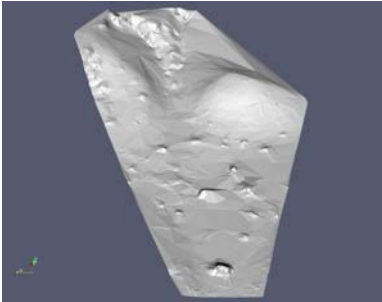


Figure 3 - Terrain Model Decimated by 70%

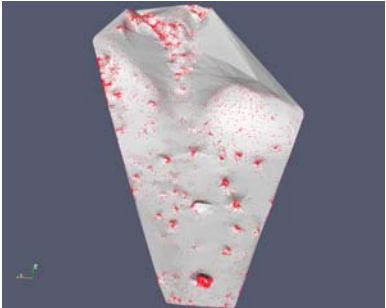


Figure 4 - Point Cloud of 70% Decimated Terrain Model Overlaid on Original Terrain Model

The decimation algorithm was also applied to an overhead map of the CSA Mars emulation terrain sampled at a 20cm horizontal resolution. In this case, the original scan contains 45301 points. The decimated scan was reduced to 9079 points, a decimation ratio of 79.8%, and the average error was then only 33.3 mm.

Figure 5 and Figure 6 show the terrain model before and after decimation for a typical terrain scan. Figure 7 shows an overlay of the residual point cloud over the triangular mesh obtained from the original point cloud. The resulting triangular-mesh of a local scan is then used for path planning.

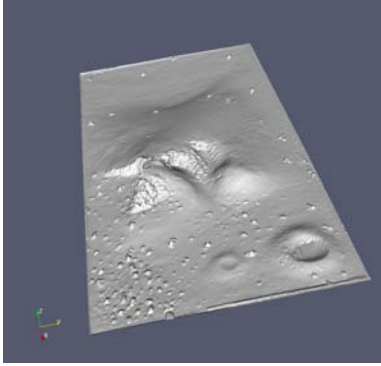


Figure 5 - Original Terrain Model

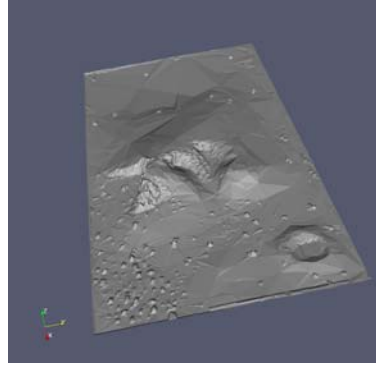


Figure 6 - Terrain Model Decimated by 79.8%

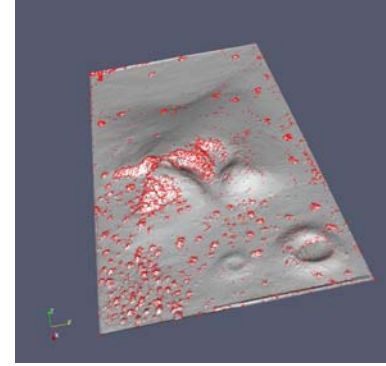


Figure 7 - Point Cloud of 79.8% Decimated Terrain Model Overlaid on Original Model

PATH PLANNING AND ROVER MOTION CONTROL

In the context of long-range navigation, the path planners used on the CSA's Mobile Robotics Testbed concentrate on finding a global solution to travel between two points in natural settings while optimizing some cost function. The basic assumption is that *a priori* knowledge of the environment is available at a coarse resolution from orbital imagery/altimetry, and that it is refined using local range sensing of the environment. The composite environment model (coarse with refined portions) is then used to plan a path that will be generally safe and that will be updated periodically as new environment data is available.

For the experiments described below, the planner used only a coarse model of the CSA Mars emulation terrain available in the form of an irregular triangular mesh. A connected graph was generated based on neighbouring triangles. Dijkstra's graph search algorithm was used to generate paths from a set of given start points to a set of target destinations. The cost function for the planner minimises total travel distance while applying a penalty for high-slope or rough terrain. A filter is applied on the generated path to remove from the trajectory waypoints that are too close together or that are co-linear.

Experimental runs were performed in the CSA's Mars emulation terrain using the CSA's Mobile Robotics Testbed (MRT): a modified Pioneer P2-AT mobile robot equipped with an inertial measurement unit. The gyroscopes in the IMU are used for precise heading measurement and wheel odometry is used to compute the travelled distance. The accelerometers of the IMU are used to correct roll and pitch with respect to the gravity vector and, at rest, a digital compass is used to reset yaw. For these runs, obstacle detection and avoidance was not activated and the LIDAR sensor was not used to generate local terrain models.

Figure 8 shows the approximate location of the points (circles in the figure) that were used as start or destination points for the planner for all runs. The points are located in the plain portion of the terrain, which is relatively obstacle-free. One of the points was located on a hill; it is worth noting that, trajectories to this point usually resulted in slippage of the wheels, thus inducing errors on distance measurements obtained through odometry.

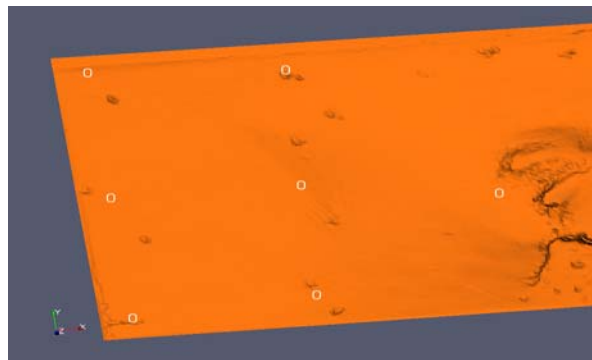


Figure 8 - Approximate Location of Test Points in the CSA Mars Emulation Terrain

Experimental runs were performed by selecting various start and destination points, planning a path on the terrain model, and executing this path using the MRT. A total of 74 paths were generated and executed using this set of control points. Figure 9 shows a typical successful experimental run.

For all runs, the robot was positioned at a start point with a known orientation and it was provided with the commanded trajectory generated by the planner. Logged data included start and destination locations, as well as the measured robot position as per the combined IMU/odometry readings. Since the robot had no sensor to detect wheel slippage, the actual error at the end of the trajectory was measured manually.

Table 2 provides a summary of the results from the path planning and motion control experiments. The success criterion used for evaluating each experimental run was the measured error between actual robot position and the destination point from the commanded trajectory. An error in position of less than 10% of the total trajectory length was considered a success; Table 2 shows that 62% of the test runs were successful. The average error among the successful runs was 4.42% with a standard deviation of 2.3% of the total trajectory length.

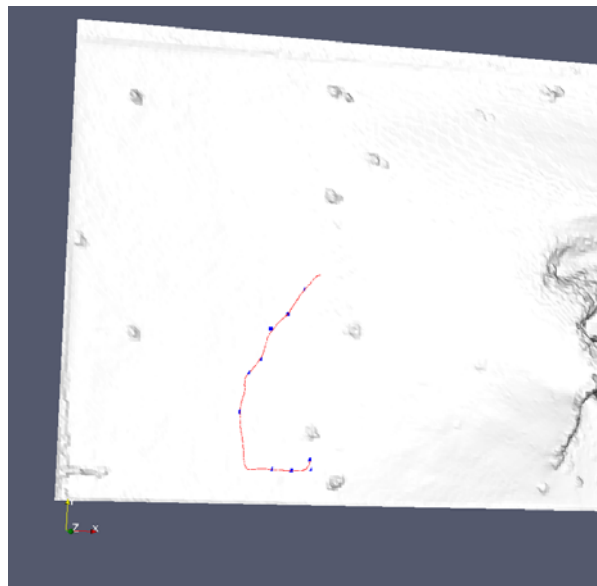


Figure 9 - Typical Path from Experimental Set. The blue squares are the path waypoints. The red line is the actual trajectory as per the combined IMU/odometry measurements

Several causes for failure were identified during the test runs. Some of these causes can be attributed to the planner/motion-control software. Examples include wheel slippage, IMU drift, and software seizures. Other causes cannot be attributed to the planner/motion-control software. Examples include the robot being bogged down in sand or bumping into obstacles that were not in the original map (obstacle detection and avoidance was turned off for the tests). Removing those failures not attributable to the planner/motion control software from the set, only 27% of the test resulted in failures. It is also important to note that the planner had a 100% success rate in finding acceptable paths. In addition, it should be noted that, in the absence of a differential GPS sensor to provide ground truth on position, the positions were measured manually using markers on the boundary of the terrain. This method has likely induced additional measurement error in the data.

Table 2 - Summary of Results from Path Planning and Motion Control Experiments

Number of tests	74
Tolerance on error (%)	10
Percent Success	62.16
Percent Failure due to Navigation	27.03
Average Error on Successful Runs (%)	4.42
Std Deviation of Error on Successful Runs (%)	2.30

LOCALISATION

The third set of algorithms for which experimental results are provided are the rover localisation algorithms. These are used for two main purposes. The first purpose is global rover localisation. In this case, it is assumed that the rover has a-priori knowledge about its immediate environment in the form of a coarse 3D terrain model. The algorithm must then match the 3D environment model acquired from the rover's point of view with the coarse model. The main difficulties with this operation reside in the fact that both 3D models are at different resolutions and are taken from different angles.

The second purpose of the localisation algorithms is to estimate the displacement between successive detailed terrain scans obtained by the rover sensor throughout its traverse. This allows the rover to correctly estimate its progression compared to the last scan, thus re-calibrating the odometry to cancel IMU drift. This knowledge also allows the mapping algorithm to stitch together detailed terrain maps to obtain a more complete 3D model of the environment. In this case, the two scans have to be partially overlapping. The scans have discrepancies in resolution since they are taken from different points of view and they also can have different occluded areas depending on the geometry of the terrain.

Two sets of algorithms have been investigated to conduct localisation. The first solution uses the Harmonic Shape Image and Spin Image algorithms in tandem, whereas, the second solution uses the point fingerprints method. The algorithms are described in detail in [5]. The experimental results obtained so far are qualitative in nature since no ground truth measurements have been used for the sensor position. The success of the localisation has been judged by examining visually the fit between the terrain model and the environment scans. In addition, there is currently insufficient data to be considered statistically representative.

The results obtained so far are based on several scans of the CSA Mars terrain. These scans were registered with models of the entire terrain sampled at different resolutions (0.2m, 0.5m and 1.0m). Figure 10 to Figure 14 illustrate some registration results using the point fingerprint-matching algorithm (similar results were obtained using spin-image matching algorithm). The results illustrate the registration of scans with models of different resolutions. These results show the ability to globally localize the rover in a natural terrain without a priori knowledge of its pose. For example, Figure 10 shows a scan that was successfully matched. The location of the sensor was estimated at the following coordinates: translation ($t_x=54.39\text{m}$, $t_y=18.98\text{m}$, $t_z=0.38\text{m}$) and rotation ($\theta_x=-0.474$, $\theta_y=-0.816$, $\theta_z=-178.29$) in degrees. Note that the CSA Mars terrain measures 60m x 30m. Its origin is on the left top corner with the x-axis pointing towards the viewer and the y-axis pointing right.

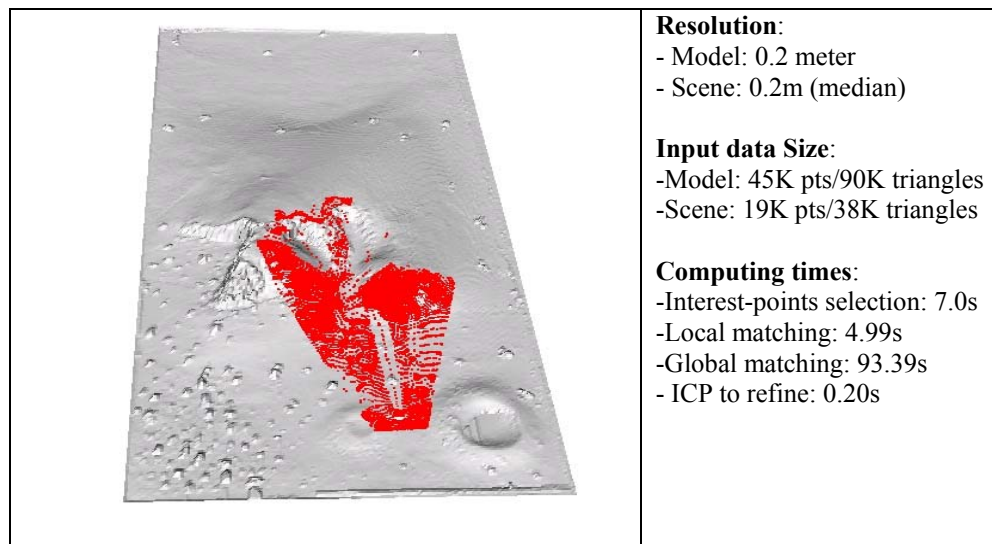


Figure 10 - Registration of Scan #1 with the 20-cm Resolution Terrain Model

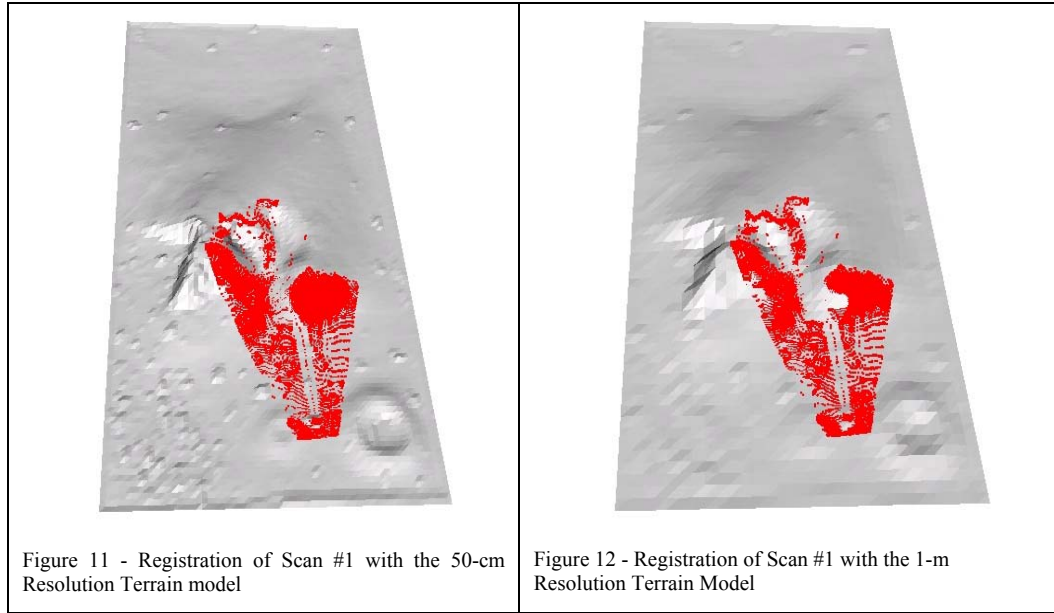
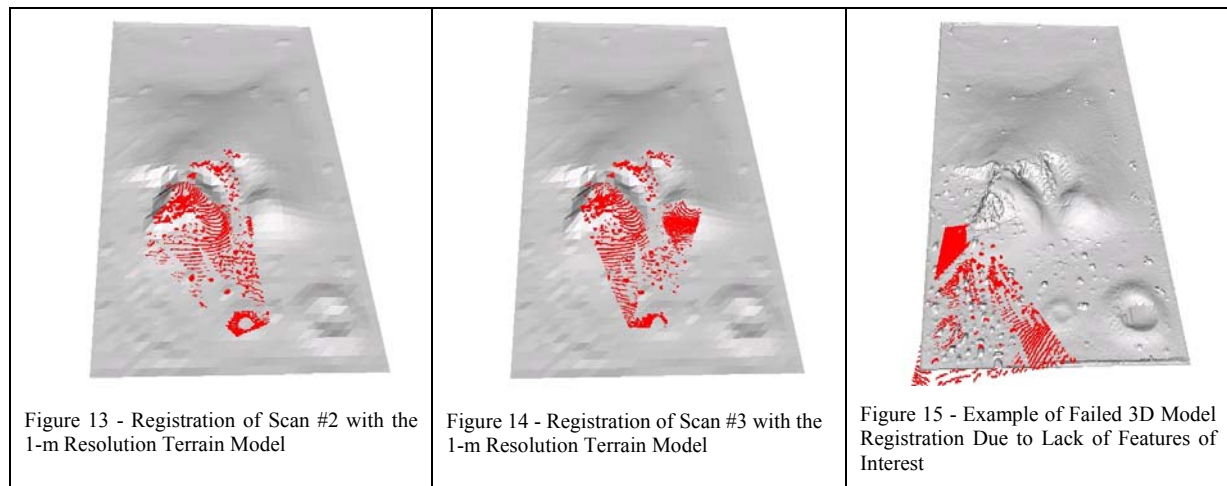


Figure 11 and Figure 12 show the results of the registration for the same scan with terrain models of 50-cm and 1-m resolution respectively. Table 3 shows the variations in the results obtained between the results associated with Figure 11 and Figure 12 and those obtained with the high-resolution terrain model (Figure 10). From these results, it appears as though the variation of the resolution of the terrain model does not affect too much the accuracy of the registration as long as the scale of the geometric features being matched is compatible with the terrain model resolution. Table 3 also leads us to believe that the computing time increases, as the resolution of the terrain model gets poorer. Experiments have not yet been run on terrain models of resolution poorer than one metre. The limit on terrain resolution for successful localisation will be dictated by the size of the features observable by the environment sensor. This is a factor of the geometry of the environment and of the sensor range. It is expected that very low-resolution terrain models will require a very long-range sensor to capture terrain features of sufficient size to enable successful localisation. The LIDAR sensor used for the experiments could be used directly since it has a range superior to one kilometre. However, such experiments will require a terrain much larger than the CSA's Mars terrain.

Table 3 - Comparative Results for Scan #1 Matching with Terrain Models of Different Resolution

Model Resolution	Δt_x (m)	Δt_y (m)	Δt_z (m)	$\Delta \theta_x$ (deg)	$\Delta \theta_y$ (m)	$\Delta \theta_z$ (m)	ΔTime (s)
0.5 meter	0.24	0.25	0.02	0.04	0.27	0.23	17.821
1.0 meter	0.03	0.33	0.08	0.09	0.43	0.32	39.9

Figure 13 and Figure 14 show the results of registration of two other scans with the 1-meter resolution terrain model. The results of the registration for scan #2 (in Figure 13) are as follows: translation is ($t_x=54.84\text{m}$, $t_y=18.55\text{m}$, $t_z=0.39\text{m}$) and the rotation is ($\theta_x=0.00$, $\theta_y=-0.68$, $\theta_z=-157.69$) in degrees. The results of the registration for scan #3 (in Figure 14) are as follow: translation is ($t_x=54.82\text{m}$, $t_y=13.95\text{m}$, $t_z=0.33\text{m}$) and the rotation is ($\theta_x=0.643$, $\theta_y=0.133$, $\theta_z=178.810$) in degrees. Figure 15 illustrates a case where the registration failed. This failure is due to the fact that the sensor data was insufficiently rich to obtain an unambiguous match with the environment model.



CONCLUSION

This paper provides experimental results obtained during the CSA's summer 2006 rover navigation test campaign. The results obtained so far have concentrated on issues related to terrain modelling, path planning and rover motion control as well as rover localisation.

Terrain Modelling using the irregular triangular mesh representation has been shown to drastically reduce the size of the data set required to model natural terrains representative of the Martian environment. It preserves the key features in the environment that are required for path planning, obstacle avoidance and localisation. Compression ratios of nearly 90% on LIDAR scans are possible with average errors in terrain modelling on the order of 40mm. A series of test traverses were performed on the CSA Mars emulation terrain using the irregular triangular mesh terrain models for path planning. The success criterion for defining successful traverses was an error in rover position lower than 10% of the total traversed distance. The failure ratio for the path planning/motion control experiments was on the order of 27%. Some failures were attributable to unstable software (resulting in crashes) or wheel slip. Additional development and experimentation will be required. Anecdotal results are also given for the localisation algorithms. A preliminary analysis of these results indicates a good success ratio in the presence of sufficiently rich sensor data (textured terrain models resulting in unambiguous matches).

At the moment, experiments are being performed to integrate all of the above-mentioned capabilities with on-board autonomy software to test “over-the-horizon” autonomous traverses.

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