AUTONOMOUS NAVIGATION FIELD RESULTS OF A PLANETARY ANALOG ROBOT IN ANTARCTICA

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ABSTRACT

The Robotic Antarctic Meteorite Search at Carnegie Mellon is developing robotic technologies to allow for autonomous search and classification of meteorites in Antarctica. In November 1998, the robot Nomad was deployed in the Patriot Hills region of Antarctica to perform several demonstrations and experiments of these technologies in a polar environment.

Nomad drove 10.3km autonomously in Antarctica under a variety of weather and terrain conditions. This paper presents the results of this traverse, the ability of stereo vision and laser scanner to perceive polar terrain and the autonomous navigation system used.

1 INTRODUCTION

From the Lunakhods on the Moon to Sojourner on Mars [6], mobile robots have demonstrated their usefulness to planetary exploration. As future missions become more ambitious, mobile robots will be required to do more tasks in shorter periods of time necessitating an increased level of autonomy. In particular, mobile robots will be called upon to drive long distances with little or no supervision to achieve the goals of planetary science.

As one of the harshest environments on Earth, Antarctica is a unique place to test planetary robotic technologies. The low temperatures, lack of communications and remoteness make it an interesting terrestrial analog of the Moon and Mars. In November of 1998, the robot Nomad (Figure 1) was deployed to the Patriot Hills region (80S, 81W) of Antarctica. This deployment was part of Carnegie Mellon's Robotic Antarctic Meteorite Search program [3] which is developing robotic capabilities to perform Antarctic meteorite searches from a mobile robot. The expedition demonstrated autonomous navigation in polar terrain and meteorite detection/classification [9]. Experiments were also performed on characterizing laser and stereo sensors [14], systematic patterned search [10], ice and snow mobility, landmark based navigation and millimeter wave radar [1]. Foot search by the expedition found two meteorites [5].

Figure 1: Nomad at the Patriot Hills

Very few robots have been deployed to Antarctica. TROV [13] and SARA [7] explored the underwater coastal regions and Dante I [15] the volcano Mt. Erebus. However, to the authors' knowledge no robot for cross country navigation in polar terrain has been demonstrated. This meant that many factors were unknown before the expedition such as the ability of stereo and laser sensors to see obstacles on snow and ice fields. This uncertainty necessitated the development of a robust autonomy system.

This paper presents a description of the autonomy system implemented on Nomad in Antarctica and presents the results of its autonomy tests.

2 NAVIGATIONAL AUTONOMY SYSTEM

The autonomy system drives Nomad through a series of waypoints while avoiding any obstacles too large for the robot to drive over. It is descended from that found on Ratler [12] and Nomad in the Atacama [16] but differs in several ways. An error recovery module has been added which lets Nomad backup and turn when it is blocked by obstacles or exceeds its roll and pitch specifications. The representation of terrain has been changed to indicate how good it is to occupy a cell and the certainty of that goodness. Finally, the laser has been fully integrated into the autonomy system. These changes have made the system more reliable and robust.

Figure 2 shows the structure of the autonomy system. Except for the controller each box is a separate Linux process running on a single Pentium Pro 133 located on Nomad. The arrows indicate interprocess communications using the Task Control Architecture's (TCA) message passing capability [11] and the arrow labels indicate the type of information passed. Messages can also be passed with TCA over a wireless ethernet link to user interface processes running on an external computer. The controller is implemented on a 68060 running VxWorks and performs the low level motor control.

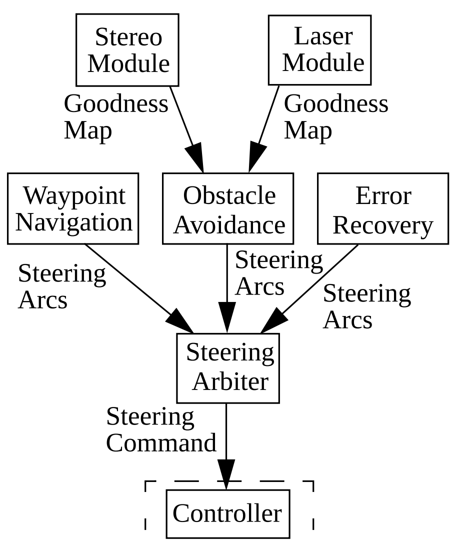

Figure 2: Autonomy System

2.1 GOODNESS MAPS

To model the environment it passes through, Nomad uses a map structure called a goodness map (an example map can be found in Figure 4). Goodness maps are fixed resolution grid based maps (Nomad currently uses a 50cm grid resolution) where each cell contains two numbers: a goodness score indicating the desirability of the robot occupying that cell and a certainty score which indicates the reliability of the goodness score. Each of these numbers are normalized between 0 and 1. Additionally, any cell with a certainty less than a lower threshold is considered unknown and certainty and goodness values are set explicitly to zero.

Multiple goodness maps can be combined by taking an average of the goodness values in corresponding cells, weighted by their certainties. If the maps are created by different sources, then a weight for the confidence in that source is also used in the average. For example, on Nomad both the stereo and laser modules create goodness maps from their sensor readings. The obstacle avoidance module maintains a local terrain map by combining these sensor produced goodness maps, weighted by our confidence in that sensor, with its own map.

Nomad only uses the perceived roughness of the terrain or traversability to determine the goodness of a cell. However, the goodness map representation is general enough to incorporate other measures in the determination of cell goodness. By using multiple criterion when determining cell goodness, a goodness map provides a unified format to balance competing goals. For example, a goodness map which combines the terrainability, science interest and the potential for solar power of a cell would help the robot make trade offs between the three criterion and choose paths which satisfy all of the constraints.

2.2 STEREO MODULE

Nomad has four Sony XC-77 640x480 B&W CCD cameras mounted on a sensor yard 1.67m above the ground at the front of the robot (Figure 3). Each camera has a Computar HAS3616APC auto iris, 3.6mm focal length lens. To operate in the cold temperatures of Antarctica the cameras are enclosed in insulated, heated boxes.

Since Nomad is quite wide and able to turn relatively sharply the four cameras are set up as two stereo pairs - one pair looking right the other looking left. They are strongly calibrated using the procedure in [8]. The raw images are first dewarped to remove radial lens distortion and then rectified so that the epipolar lines lie on the scan lines.

To reduce the cycle time only a small number of rows in the image are examined by the stereo module. These rows correspond to distances of 4.5m to 8.5m in front of the robot. The stereo module computes the disparity map in this region and takes the (x,y,z) pixel coordinates to create a goodness map by using a plane fitting technique. For each cell in the goodness map, stereo fits a plane to the data in a region equal to the size of the robot (a 5x5 grid cell area) centered at the active cell. Smaller planes are also fit to each cell in this 5x5 submap. The goodness score of the center cell is then determined by the roll and pitch of the planes as well as the residual from fitting the planes. The certainty is derived from the number of data points used to create these planes. This process produces a goodness map where the goodness of a cell is the lowest goodness of all cells in a 5x5 area. Therefore obstacles are expanded into configuration space format allowing planning to consider Nomad as a point robot [4]. The goodness map created depends only on the current stereo image.

Figure 3: Nomad's sensor yard with 4 CCD cameras and SICK LMS 220 single line scan laser unit.

2.3 LASER MODULE

Nomad uses a SICK LMS 220 single line scan laser unit as a second sensor to detect obstacles. It is capable of generating distance measurements in a $180°$ field of view in increments of $0.25°$. In practice, the autonomy system uses a scan of $100°$ in increments of $1°$.

The output of the laser module is a goodness map which indicates the terrainability of the map squares illuminated by the laser sensor. The goodness map is created by first fitting a line to the complete laser scan using a least squares method. This line is considered as the ground. Next, the deviation of each laser measurement from the ground line is computed. The goodness of a cell is then inversely proportional to the average deviation of all the laser measurements in the cell. Cell certainty is proportional to the number of measurements present in the cell. Cells with goodness values below 0.5 are expanded to fill the 5x5 cell area around them, providing configuration-space obstacles in the map [4]. A large change in the level of the ground line from the previous scan indicates a step feature - such as a cliff - so in this case all map cells with laser measurements are marked with low goodness. Other than the previous ground level, the goodness map produced is based entirely on the current scan.

2.4 OBSTACLE AVOIDANCE

The obstacle avoidance module, named Morphin, is the heart of the navigation system. It maintains a goodness map of the environment around the robot. This map is generated by merging the goodness maps created by the stereo and laser modules. Unlike the sensor goodness maps, Morphin's map contains data from previous sensor module maps. When a new sensor module map arrives Morphin ages its current map by multiplying the certainties of each cell by a number less than 1. It then merges in the new data using the cell certainties and sensor type to weight each goodness value. In this way new data is added to Morphin's world view and older data becomes less sure until finally it disappears from the map.

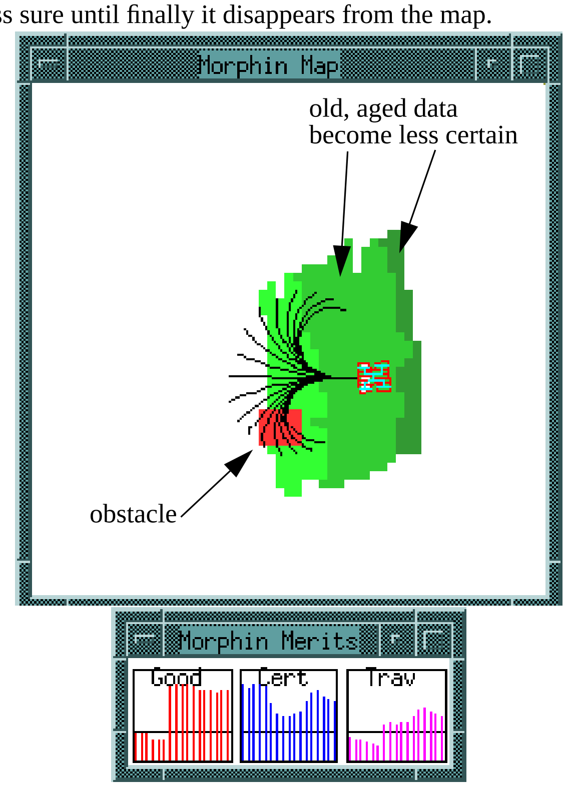

Figure 4:Morphin goodness map with potential driving directions. The votes for each driving direction are indicated by the height of the bars in the Trav window.

Using its goodness map, Morphin evaluates a set of steering arcs. The arcs represent how Nomad would travel on the terrain if it were next commanded to steer in a given direction. Since Nomad turns slowly relative to its nominal travel speed of 30cm/s, Morphin takes steering latency into account when computing travel paths. Each arc is given a score on how good it is to travel along it. If an impassable obstacle is present along the path, the arc is vetoed. The arc votes are then sent to the steering arbiter.

A typical Morphin goodness map with driving arcs and their votes is shown in Figure 4. The map displays the goodness values as different colors and the certainty as different brightnesses. The dark square at the bottom left is an obstacle, expressed in configuration space. Older data is aged or made less certain. This is shown by the darkening of the cells from left to right (the robot is driving to the left). The arcs which Morphin evaluates are drawn over the map starting at the current vehicle position. The Morphin Merits window below the map shows the sum of the goodness and certainty along each arc in the Good and Cert frames. The Trav frame combines the two criterion and is the final vote from Morphin for each arc. Votes below the horizontal line indicate vetoed arcs, and correspond to those arcs passing through the obstacle.

2.5 WAYPOINT NAVIGATION

The waypoint navigation module takes a list of differential global positioning system (DGPS) coordinates as input from a remote human operator. Waypoint prefers Nomad to drive straight towards the current waypoint. It generates votes on the same set of steering arcs as Morphin. The magnitude of the votes are distributed as a Gaussian centered in the direction of the goal. These votes are then sent to the steering arbiter. Once the robot's position is within some specified error radius of a waypoint, the next point in the list becomes the current goal.

2.6 ERROR RECOVERY

The error recovery module has two purposes. The first is to monitor the status of the robot, detecting when a problem has arisen. The second is to initiate an action that will help solve the problem.

In its current form the error recovery module is able to monitor for two problems. The first is when the robot is unable to move because all of the possible travel directions are vetoed due to obstacles. The second is to monitor the roll and pitch of the vehicle to determine when the robot has driven on bad terrain missed by the terrain sensors. This second mode is also referred to as blind driving.

If either of the two problems is detected, error recovery will suspend Morphin and waypoint navigation and initiate a back up maneuver. This causes the robot to back up along its previous route (since Nomad has no sensors looking back this is the safest way). After a fixed time backing up, Nomad will turn in the direction opposite to where it had been driving and then re-enable Morphin and waypoint navigation.

2.7 STEERING ARBITER

The steering arbiter takes the votes provided by Morphin, and the waypoint navigation modules and combines them to decide on Nomad's actual steering direction. Each module is given a weight indicating its importance. If any module vetoes an arc, arbiter will not select that arc. The arc with the highest vote is chosen and an appropriate steering command is issued to the controller.

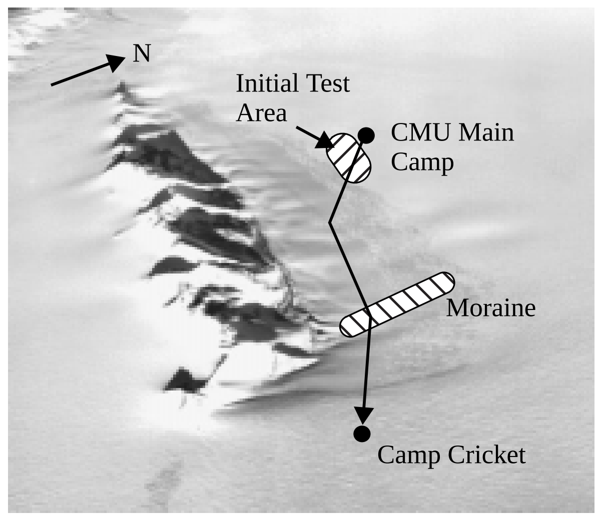

Figure 5: Patriot Hills, Antarctica. The map shows the major areas of operation and the path is Nomad's autonomous trip to the east end of the hills.

3 EXPERIMENTAL RESULTS

The autonomy system described in section 2 was tested on Nomad at Patriot Hills, Antarctica. Patriot Hills contains examples of three common Antarctic terrain types: snow, blue ice and moraine. The snow fields generally consist of hard packed snow which has been sculpted by the wind to form small dunes called sastrugi. Most sastrugi in the area were 10 to 20cm in height allowing Nomad to drive over them without difficulty. The blue ice fields are generally very flat with small (5cm diameter) depressions, called sun cups, covering the surface. Moraines are the most difficult terrain for robot navigation but also the most interesting for meteorite search. Moraines are areas on the blue ice fields where there are large collections of rocks. Rock size and density varies depending on the moraine but the Patriot Hills moraine was sparsely distributed with most rocks being 40cm or more in diameter and posing a hazard to Nomad.

Taking advantage of Patriot Hills' varied terrain, Nomad's autonomy system was tested in all three terrain types, driving autonomously for a total of 10.3 km during the expedition. Of this distance, 4.7 km was spent driving in the snow field south of the main camp and the moraine. The remaining 5.6 km was made up of the trek from the main camp to the east end of the Patriot Hills (Figure 5).

3.1 EVALUATION OF TERRAIN SENSORS

The ability of a robot to sense its environment is an important capability for autonomous navigation. Thus an important component of Nomad's autonomy tests was the evaluation of its terrain modeling sensors - stereo and laser - in the different terrains and weather conditions of Antarctica.

As on the physical parts of the robot, Antarctica is harsh on traditional outdoor robotic terrain sensors. Sensors must be placed inside sealed, heated enclosures to prevent damage from snow and cold. The reflective property of the ground varies from the Lambertian snow fields to the specular blue ice fields and everywhere the color is an almost uniform white or blue.

During Nomad's tests in the Atacama and Pittsburgh, stereo provided the most information to the navigation system. This was because it provided terrain information from an area rather than just the single line from the laser. The stereo system was tested on snow, blue ice and moraine at the Patriot Hills as well as in three different weather conditions: sunny, cloudy and blowing snow. In all conditions stereo was not able to produce sufficiently dense disparity maps to be useful for navigation. Polarizing filters did improve performance on blue ice but still results were not sufficient for navigation. The terrain type had very little effect on the results (the moraine was sparse enough that most of a scene would be blue ice and not rocks). The weather however did have a large impact on the stereo results. Sunny days provided the best results with blowing snow a close second. Overcast conditions proved the most difficult for stereo. The clouds diffused the sunlight which, combined with the Lambertian surface of a snow field, made the illumination almost uniform everywhere. There was no contrast and it was very difficult, even for humans, to see depth. This phenomenon is referred to as a white out in [2]. During these conditions stereo was able to match very few points.

The single line scan laser unit was tested in the same conditions as the stereo system. The laser was unaffected by terrain type working as well in Antarctica as in pre-trial tests in Pittsburgh. Even the specular surface of the blue ice fields had no effect on the return signal. Overcast conditions also had no effect on the active laser sensor. The laser did, however, have problems during periods of blowing snow. The laser could reflect off the snow flakes. If it reflected back to the laser unit a short distance would be measured. If it reflected away, no return signal would be received. During mild levels of blowing snow filtering was able to remove these effects. However in heavy storms, filtering did not work and the laser could not be used.

A more complete presentation of sensor results from Antarctica can be found in [14].

3.2 EVALUATION OF NAVIGATION AUTONOMY

For the duration of the expedition, stereo did not provide enough information to use in navigation and obstacle detection. Thus all of the navigation results were obtained using only the single line scan laser for obstacle detection. The navigation system was robust enough to handle the absence of stereo with only small changes to a configuration file of Morphin (unknown terrain's negative impact to an arc's score was reduced to zero).

The first set of navigation tests were performed on the snow fields near the main camp. During these tests the waypoint navigation module was given four waypoints in a rectangle 50x100m. Nomad continually drove around this course. Periodically, a human "volunteer" would step in front of Nomad. Since the laser sensor does not look far enough ahead to allow Nomad to turn and avoid an obstacle Morphin would veto all arcs when the person was seen. This would trigger the recover module which started a backup maneuver. Nomad successfully saw people, backed up, turned, drove past them and then resumed its rectangular course.

After these initial tests, Nomad embarked on a trek to the eastern end of the Patriot Hills. The trek proceeded in two segments. The first, from the main camp to the moraine, used the laser as its only sensor. The second leg, from the moraine to Camp Cricket, was performed during heavy snow which made the laser useless. The error recovery module's blind driving mode was the only sensor in use.

Since the moraine offered the highest density of impediments to travel for Nomad, several tests were performed there. Using only the laser, Nomad was commanded to drive to various places in the moraine. During these tests, Nomad encountered 12 rocks. It saw, and successfully avoided 9 of them. The other 3 rocks were not seen and required using the emergency stop button. These three rocks were missed because they got between the laser and the robot while Nomad was making a sharp turn.

4 CONCLUSIONS

Antarctica is a challenging environment for autonomous mobile robots and terrain sensing modalities. Stereo vision works poorly or not at all here. The vast majority of the terrain is made up of snow and ice fields which provide little texture for disparity matching. Stereo is further hampered in overcast conditions where the diffuse nature of the light eliminates all contrast, making it difficult even for human vision to work. The laser sensor works well on all terrains but heavy blowing snow reflects the beam causing false readings.

Despite the absence of stereo data, the autonomy system on Nomad was robust enough to drive 10.3km, detecting and avoiding several rocks with just the laser sensor. Nomad was driven on three major terrain types, snow, blue ice and moraine and in all weather conditions. The tests performed demonstrated the capability of autonomous navigation in polar terrains which is an essential component in the robotic search for meteorites in Antarctica.

Performance of the autonomy system can still be improved. Morphin should consider unknown terrain between the robot and the laser scan to be untraversable. This will help solve the problem of unseen obstacles getting between the laser scan and the robot during sharp turns. Another solution to this is to actively tilt the laser providing a scan over an area instead of just a line.

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