A Terrain-Based Path Planning Method for Mobile Robots

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Abstract. *This paper presents a technique for incorporating terrain traversability data into a global path planning method for field mobile robots operating on rough natural terrain. The focus of this approach is on assessing the traversability characteristics of the global terrain using a multi-valued map representation of traversal difficulty, and using this information to compute a traversal cost function to ensure robot survivability. The traversal cost is then utilized by a global path planner to find an optimally safe path through the terrain. A graphical simulator for the terrain-based path planning is presented. The path planner is applied to a commercial Pioneer 2-AT robot and field test results are provided.*

I. Introduction

To enable long-range traverse of mobile robots on hazardous terrain, global path planning methodologies must be utilized to ensure goal achievement. The process of planning global paths for robots operating on high-risk access terrain is a difficult task. In order to allow successful completion of robotic exploratory missions, intrinsic properties of the terrain must be directly integrated into the path planning logic. Global terrain features that are risky for mobile robot traversal must be identified and paths must be planned to circumnavigate unsafe regions. By analyzing terrain characteristics before traversal, global paths can be constructed that will minimize risk to the robot and ensure robot survival, and ultimately mission success.

To address this problem, we have developed a methodology that uses a safe path constraint to connect start and goal locations based on terrain features. Global terrain attributes are first analyzed and used to segment the terrain into regions of different traversability using the concept of the traversability map, a multi-valued map representation that denotes the ease-of-traversal of different regions of the terrain. Information from the traversability map is then utilized to compute a traversal cost function to ensure robot survivability. A global path planner incorporates the cost function into a search methodology to find an optimally safe path through the terrain.

The following sections describe the methodology in detail. Section 2 gives an overview of related research. Section 3 discusses the terrain-based path planning method, and Section 4 describes the graphical simulator used to implement the method. Section 5 provides experimental results of the method driving a Pioneer 2-AT robot. Conclusions drawn from this work are reported in Section 6.

II. Background

Traditional path planning methods [see, e.g., 1] typically segment the terrain using a grid representation and plan paths using the concept of goal attainment as the driving force, while avoiding obstacles. Terrain traversability is characterized by assigning to each grid cell a binary value, where 0 denotes an impassable cell containing an obstacle, and 1 represents an obstacle-free passable cell. Alternatively, a continuous value that represents the probability distribution for occupancy of the grid cell by an obstacle can be assigned [2]. Approaches such as these account for obstacle presence, but disregard intrinsic terrain properties. There have been some efforts in developing regional planners that overcome these limitations [3,4]. These efforts (D* and RoverBug) fall under the category of sensor-based motion planning in which the robot analyzes terrain slope and roughness with on-board sensors. These algorithms construct local path segments based on the sensed environment and use this information to plan paths in an incremental fashion.

An approach developed by Murphy et al [5] plans paths based on terrain preferences. In this approach, a wavefront propagation type planner algorithm is used, which incorporates terrain preferences using different weighting factors. However, the manner by which the terrain traversability factors are determined is not addressed. Shiller [6] uses terrain topography and simple vehicle dynamics to generate a global optimal path on a general terrain. Shiller measures traversability by using velocity limits based on dynamic vehicle constraints and a mesh of cubic splines to represent the terrain. Our approach is similar to these methods in that we utilize a *gradual gradation* of the terrain traversability in the path planning process. The main difference is in the

representation of the traversability measure, which employs a robust perceptual representation of the terrain quality called the Fuzzy Traversability Index [7-8]. In this approach, traversability is calculated from fuzzy descriptors of terrain characteristics extracted from visual imagery data. The traversability index can assume any numeric value in the continuous range {0.0, 1.0}. This Traversability Index is represented by the four fuzzy sets {*POOR, LOW, MODERATE, HIGH*} that correspond to unsafe, moderately-unsafe, moderately-safe, and safe terrain segments, respectively (Figure 1). Each terrain segment is assigned a traversability index depending on its characteristics, which grades the level of risk associated with traversing over the given region. Based on this fuzzy representation of terrain traversability, the safest path is planned to minimize the traversal risk. Waypoints through these regions are calculated and sent to a regional sensor-based navigation algorithm which determines the safest segment to traverse through each selected region based on cameras on-board the robot. During traversal, a local hazard avoidance algorithm ensures that the robot circumnavigates local hazards.

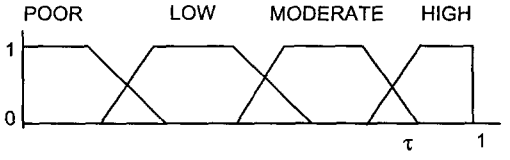


Figure 1. Traversability Index representation

III. Terrain-Based Path Planning

The approach developed here is based on integrating two main concepts: traversability map building and global terrain-based path planning (Figure 2).

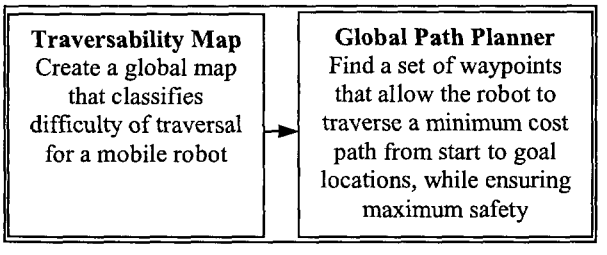


Figure 2: Overview of terrain-based path planning algorithm

The Traversability Map represents the ease-of-traversal of the global terrain. Thus, the traversability map-building process involves identifying major terrain features (such as hills, lakes, valleys) as observed in images obtained during prior aerial imaging or land surveying. These image collections allow for planning at different scales of resolution. This terrain information is passed onto the traversability map-building algorithm, which assigns traversability indices based on terrain characteristics using a fuzzy-logic rule-based system [7-8]. For example, a crater edge can easily be designated as untraversable, and thus will receive a POOR traversability index, whereas a hill, depending on its slope, may receive any value associated with POOR to MODERATE traversability. A typical rule set will thus be:

IF *Plateau* is **Present** and *Roughness* is **Smooth,**
THEN *Traversability* is **High**

IF *Hill* is **Present** and *Roughness* is **Smooth,**
THEN *Traversability* is **Moderate**

IF *Plateau* is **Present** and *Roughness* is **Rocky,**
THEN *Traversability* is **Low**

IF *Crater Edge* is **Present,** THEN *Traversability* is **Poor**

The outcome of this algorithm is the Global Traversability Map, which is represented by regions of different traversability indices. Figure 3 shows two example images of computing the Traversability Map based on visual imagery using this fuzzy-logic construct. In Figure 3, safe cells are represented by white, unsafe cells by black, and gray-level cells represent traversability indices in-between.

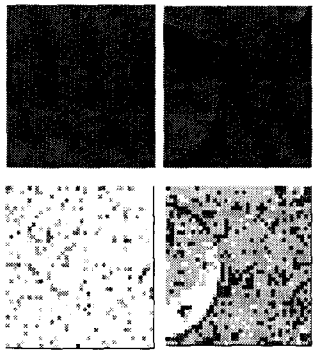


Figure 3: First row: original image; Second row: Traversability Map

A grid map based on the traversability map is then constructed in which each grid cell[1] is assigned the *minimum* traversability value of any region encompassed by that cell. This ensures that a cell is marked untraversable if any part of the cell is untraversable.

Once grid traversability indices are computed, the derived terrain characteristics can be directly incorporated into the

[1] The cell's dimension is comparable to the robot's physical size.

global path planning strategy to enable long-range traverse of mobile robots. This is accomplished by using a search algorithm to find a path from the robot's start position to a designated goal position, while ensuring robot survivability. The inputs to the search algorithm are thus the traversability grid map, the robot's initial position, and the desired destination. The output from the algorithm is a continuous path, designating a minimal traversal cost path from the start position to the goal location.

The focus of the global path planning algorithm is to find a path that minimizes our traversal cost function. Given the robot's initial position and destination, and the traversability grid, an A* search strategy [9] is implemented to determine the sequence of waypoints necessary for goal achievement. A* attempts to find the optimal path which minimizes the total traversal cost by combining the advantages of two search techniques known as *best first* search and *breadth first* search [10]. Breadth first search attempts to find the best path by looking at solutions with minimal cost from the initial start location, whereas best first search attempts to guess at the best optimal solution by using heuristics. The A* search algorithm thus assigns to each possible solution a combination of the cost of the path traversed so far and the estimated cost to the goal position. A* is classified as a heuristic-based search method that searches through the solution space by minimizing a user-defined cost function. Each grid cell represents a possible node to be searched and is given an associated cost value. This cost function is based on maximizing safety (traversability index) and minimizing the path length for goal attainment. For our application, this cost function is defined as:

$$C = \alpha \sum \frac{1}{\tau_i} + \beta \sum l_i$$

where τ_i is the numeric value of the traversability index of cell i, $1/\tau_i$ represents the cost associated with traversing cell i, and l_i is the distance from the goal cell position to cell i's position in the grid map. In our current implementation, we use a grayscale representation for the Traversability Index τ_i with values in the range (0,255). This range is subdivided into four sets: (0,80) for POOR, (45,150) for LOW, (115, 220) for MODERATE, and (175,255) for HIGH.

The relative values of α and β represent the aggressiveness of the traversal cost function, where aggressive is related to the willingness of the system to take risks. For an aggressive cost function, α is chosen low and β is chosen high; whereas for a conservative function, α is high and β is low. The rule-base is designed to prefer safe paths. In other words, to arrive at the destination safely is more important than trying to find the shortest path through the terrain. The weights α and β can be adapted based on user constraints. For example, if safety is as equally important as path length, both α and β can be given equivalent numerical values. Under no circumstances do we allow the robot to traverse UNSAFE terrain since this characterizes a POOR traversability region in which there is unacceptable risk to the robot.

Once a safe path is constructed using the search method, waypoints are calculated and sent to a real-time navigation algorithm embedded on-board the robot. These waypoints are calculated based on a specified traversal distance provided by the user. For example, if the user sets the traversal distance at 5 meters, the waypoints are calculated such that the distance between two adjacent waypoints equals 5 meters.

IV. Path Planning Graphical Simulator

The Graphical Simulator provides a tool for visualization and testing of the capabilities offered by the terrain-based path planning method described in this paper. The simulator is written as a Java application for platform independence, and runs on PCs as well as on Sun Unix machines. A snapshot of the graphical interface is shown in Figure 4.

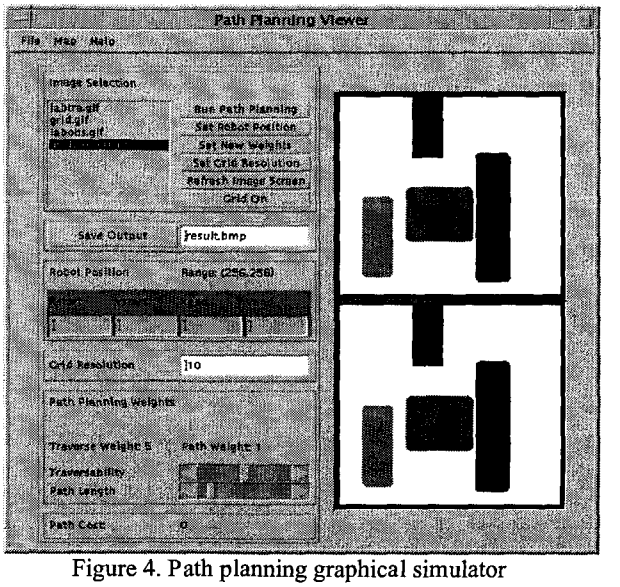


Figure 4. Path planning graphical simulator

The main components of the graphical simulator are:

- A graphical user interface that includes selectable options used by the planner.

- A terrain image viewer/editor that displays terrain maps and resulting paths.

The first step in the path planning process is selecting a terrain map of interest. Grayscale images are used to represent the traversability indices, which correspond to terrain features, and are denoted using a range of grayscale pixel values. A pixel value of 255 (white) represents a terrain region that is safe for robot traversal, whereas a pixel value of 0 (black) represents terrain that is unsafe, resulting in unacceptable risk to the robot. Values in the range (0,255) correspond to varying degrees of terrain safety. A user can select different terrain images for path planning purposes using the graphical simulator, or the user can interactively add or remove traversability regions from the displayed image map.

The next step in the process is to populate the user-selectable options, which parameterize the path planner's performance. The selectable options include:

- Set Weights
  - Select values for the α and β weights used in the traversal cost function *C*.
- Set Grid Resolution
  - Segment the image scene into individual grid cells. The higher the resolution value, the faster the search process.
- Set Robot Positions
  - Specify robot initial position and destination.

A Java program is written to implement the A* algorithm discussed previously using the cost function *C*. Once all options are entered, the user can run the path planner, at which point the image scene is segmented into individual grid cells using the grid resolution parameter and a cost is associated with each cell. The cost value is then used to find the optimal safest path that links the robot's start and goal positions. Finally, the path planning results are graphically displayed to the user.

V. Field Tests

We utilize the Path Planning Graphical Simulator to construct safe paths for a mobile robot operating on rough terrain. Figure 5 shows snapshots of the field test site used for testing the path planning method with a commercial Pioneer 2-AT mobile robot. Figure 6 shows the corresponding traversability map of the test site derived by land surveying. In Figure 6, the white, light gray, dark gray, and black regions have HIGH, MODERATE, LOW, and POOR traversability indices. respectively. The chosen site covers an area of 29m by 38m and contains regions of rocky hills, steep slopes, and flat sandy zones. In this paper, we present two case studies to demonstrate the capabilities of the terrain-based path planning method for mobile robots. The path planning simulation result for the first case study is shown in Figure 7a, and the second case is shown in Figure 7b. In the first case study, the goal position is selected at a point located 16 meters in front of the starting location. There are only two feasible paths for goal achievement. The mobile robot can traverse through a moderately-safe (light gray) passageway situated in-between two unsafe hill regions, or the mobile robot can choose to circumnavigate the entire area and travel through a completely safe region (white). Figure 7a shows that the planner selects an optimally safe path that traverses through the hill regions, thus ensuring robot safety while minimizing distance traveled. For case study two (Figure 7b), the goal is located at 30 meters in front and 5 meters to the right of the initial robot location. In this case, the mobile robot circumnavigates the unsafe areas while far from the goal, but chooses to traverse through a risky area when it is positioned within 5 meters of the goal. In this situation, the close distance to the goal outweighs the weighting of the traversability index. As seen in both case studies, in no circumstance is the path chosen to traverse through unsafe regions with POOR traversability indices (black regions).

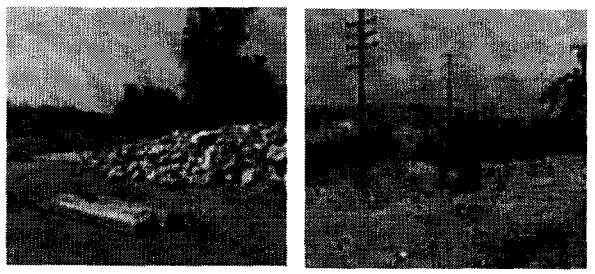


Figure 5. Field test site photos

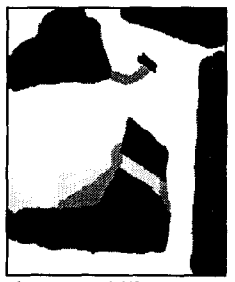
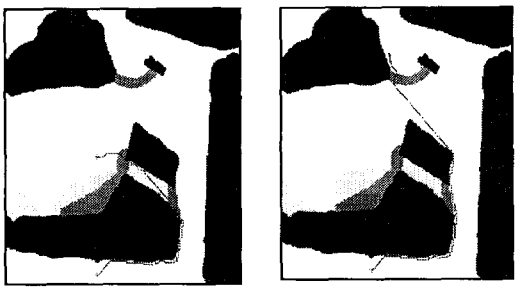


Figure 6. Derived traversability map from land survey

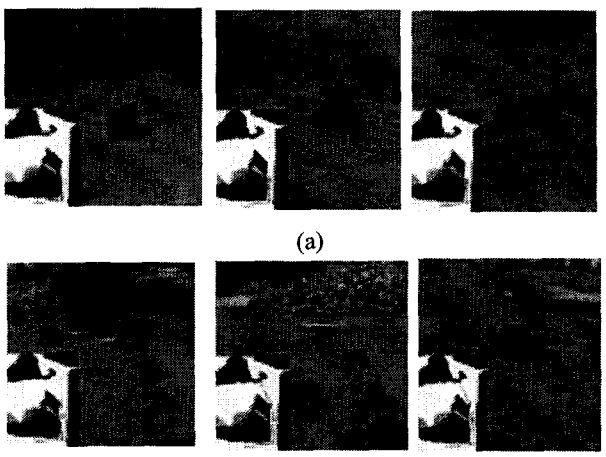
Once we demonstrate the capabilities of the path planner using the graphical simulator, we test the two case studies using the physical robot. Waypoints calculated from the planned path are forwarded to the mobile robot traversing the field. The mobile robot, a Pioneer 2-AT, uses an electronic compass device to determine absolute robot heading relative to the selected waypoint. This allows for

correction in the position estimation typically computed using wheel encoder readings, and thus improves system accuracy when verifying waypoint attainment. Figure 8a shows snapshots of the robot traversal corresponding to case study one, while Figure 8b corresponds to case study two. The inset shows the robot position relative to the planned path on the simulator screen. In both field tests, the robot successfully follows the path generated by the terrain-based path planner and safely reaches the goal position.



(a) (b)

Figure 7. Global path planning results from case studies



(a)

(b)

Figure 8. Field test photos of rover traversal (a) case study one, (b) case study two

VI. Conclusions

In this paper, we present an approach that uses the concept of the traversability map to incorporate terrain characteristics into the path planning process in order to plan safe paths on hazardous terrain. The utilization of the traversability index is shown to provide a natural terrain representation, which is necessary for planning safe paths in rough terrain. This framework is particularly suitable for planning paths for planetary robots that must operate safely in high-risk access terrain.

VII. Acknowledgment

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VIII. References

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