A Real-Time Autonomous Rover Navigation System

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ABSTRACT

To enable real-time autonomous navigation, a mobile robot is equipped with on-board processing power, image-processing algorithms, and a fuzzy computation engine that allow the rover to safely navigate to a designated goal while avoiding obstacles and impassible terrains. The underlying architecture discussed in this paper utilizes real-time measurement of terrain characteristics and a fuzzy logic framework for on-board analysis of terrain traversability. The overall navigation strategy, consisting of terrain-traverse and goal-seeking behaviors, requires no *a priori* information about the environment, and uses the on-board traversability analysis to enable the rover to select easy-to-traverse paths to the goal autonomously. The rover navigation system is tested and validated with a set of physical rover experiments. These experiments demonstrate the real-time capability of the navigation system.

KEYWORDS: Traversability, Rover Navigation, Fuzzy Logic

INTRODUCTION

Exploration of planetary surfaces by autonomous mobile robots offers several technical challenges. Planetary rovers must have the ability to operate autonomously and intelligently on challenging terrains with minimal interaction with human operators. The rover must have "on-board intelligence" needed for long-range traverses in highly-unstructured and poorly-modeled natural terrains. Their on-board intelligence must be capable of real-time navigation and motion control based on poor and noisy sensory data. To this effect, the rover must possess the ability to navigate a path to a specified goal, in the presence of sensor uncertainty, while not exposing the rover to any undue risk.

The development of a comprehensive system for robust and safe navigation of planetary rovers operating on challenging terrains has been inadequately addressed in previous research efforts [1-4]. To address this issue, an on-board rover navigation system for mobile robots operating on natural terrains has been constructed. Based on the physical properties of the terrain (such as slope and roughness), the suitability of the terrain for traversal is represented using a recently developed Fuzzy Traversability Index [5]. The terrain's physical properties are extracted from the images obtained by a triple pair of stereo cameras capable of viewing the 180° region located in front of the rover.

The use of the fuzzy traversability index allows the terrain assessment algorithm to directly account for sensor uncertainty and noise while still maintaining its robustness. The outcome of the assessment algorithm is directly incorporated into a set of fuzzy navigation rules that physically guide the rover toward the safest and the most traversable terrain. This rule set is integrated with fuzzy rules for goal seeking to construct an autonomous navigation strategy for a mobile robot that requires no *a priori* knowledge about the environment. The following sections gives an overview of this real-time autonomous navigation system.

NAVIGATION BASED ON TERRAIN CHARACTERISTICS

In a recent paper [5], the concept of the Fuzzy Traversability Index is introduced as a simple measure for quantifying the suitability of a natural terrain for traversal by a rover. Two important attributes that characterize the difficulty of a terrain for traversal are the slope and roughness of the region. The Traversability Index can thus be defined in terms of these two physical variables.

Terrain Roughness: The terrain roughness β is represented by the linguistic fuzzy sets {SMOOTH, ROUGH, ROCKY}, with the trapezoidal membership functions shown in Figure 1. The terrain roughness is derived directly from the rock size and concentration parameters of the associated image scene. First, an algorithm for determining the rock size and concentration of a viewable scene is applied to a pair of *uncalibrated* stereo camera images [6]. These inputs are characterized by the trapezoidal linguistic fuzzy sets {SMALL, LARGE} for size and {FEW, MANY} for concentration, and are used as inputs into the fuzzy rules summarized in Table I.

Table I. Fuzzy rules for roughness | Figure 1. Fuzzy membership functions: Terrain Roughness
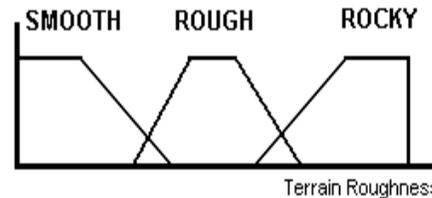
Terrain Slope: The terrain slope α is represented by the linguistic fuzzy sets {FLAT, SLOPED, STEEP}, with the trapezoidal membership functions shown in Figure 2.
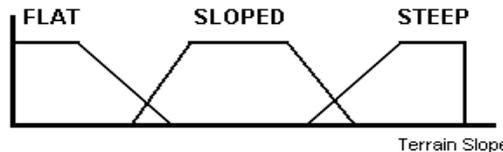
Figure 2. Fuzzy membership functions for terrain slope.

To obtain the slope from a pair of stereo camera images, the real-world Cartesian x, y, z components of the ground plane boundary are first calculated as in [6]. These points are then used as inputs into the following slope equation:

$$slope = \frac{1}{N} \sum_{i}^{N} atan2(z, x) \qquad (1)$$

Traversability Index: Once the slope α and roughness β parameters are calculated, the Traversability Index τ is computed in order to classify the ease of terrain traversal. The Traversability Index τ is represented by the linguistic fuzzy sets {LOW, MEDIUM, HIGH}, with the trapezoidal membership functions shown in Figure 3. The Traversability Index τ is defined in terms of the terrain slope a and the terrain roughness b by a set of simple fuzzy relations summarized in Table II.

ROUGHNESS	SLOPE		
	FLAT	SLOPED	STEEP
SMOOTH	HIGH	MED	LOW
ROUGH	MED	LOW	LOW
ROCKY	LOW	LOW	LOW
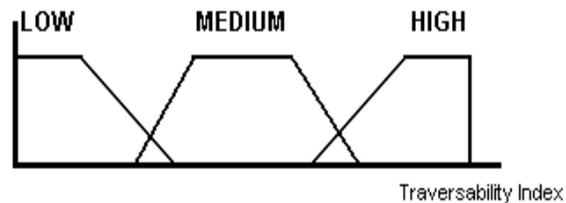
Table II. Fuzzy rules: Traversability Index   Figure 3. Fuzzy membership functions: Traversability Index

Terrain-Based Navigation Rules

Terrain-based navigation rules are developed to *safely* navigate a rover from a known initial position to a user-specified goal position. The basic idea behind the terrain-based navigation rules is that the rover tries to:

- Rotate to face the terrain region with the highest Traversability Index, i.e., the safest and the most traversable region is chosen.
- Adjust its speed based on the quality of the terrain to be traversed in order to ensure rover safety and avoid damaging the rover.
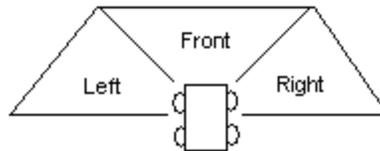
Figure 4. Partitioning of traversability regions

The terrain in front of the rover is partitioned into three 60° sectors covering a distance of up to about 5 meters in range (Figure 4). The Traversability Indices for these regions are computed from the measurements of the terrain slope and roughness as described above. The on-board software then uses the fuzzy rule set to compute the three traversability measures and to select the most traversable region. Once the direction of traverse is chosen, the rover speed can be determined based on the value of the Traversability Index for the *selected* sector. A set of fuzzy rules for terrain-based navigation can be found in [5].

GOAL-BASED NAVIGATION RULES

Goal-based navigation involves navigating the robot from its current position to the desired goal position. The basic idea behind the navigation rules is that the robot tries to: (1) approach the goal with a speed proportional to the distance between the current position and the goal position, and (2) rotate toward the goal position by nullifying the "heading error", which is the angle by which the robot needs to turn to face the goal directly. A set of fuzzy rules for goal-based navigation can be found in [5].

BEHAVIOR INTEGRATION

Once the recommendations from the terrain-based and goal-seeking navigation algorithms are generated, they must be integrated to form a unified autonomous navigation strategy. This task is accomplished by using appropriate weighting factors to construct the combined, coordinated control actions for the rover navigation. A method for behavior integration is described in [5].

EXPERIMENTAL SYSTEM

Figure 5. Pioneer AT Mobile Robot with enhancements

The Pioneer AT (All-Terrain) Mobile Robot is used to host the navigation algorithms and test the real-time decision-making capability of the navigation behaviors. A trailer is fabricated in-house and is attached to the back of the Pioneer to carry the on-board computer chassis and a second battery. Figure 5 shows the enhanced Pioneer rover, together with on-board processing power, two 4-input framegrabber boards, and six CMOS NTSC video cameras. Figure 6 shows the physical layout of the camera platform. The cameras are placed such that the lens centers are 740mm above the ground, the optical axis of each camera is tilted down by $8°$, and the intersecting origin of all cameras is centered above the rover wheels. In addition, the stereo baseline length is set to 500mm. Figure 7 shows the positions and orientations of all six cameras on the horizontal plane. This camera placement scheme provides the rover a viewable distance of about 5 meters, which is derived from the following equation [9]:

$$d = \sqrt{\frac{b * r}{p}} \qquad (2)$$

where *b* is the stereo baseline, *r* is the stereo pixel resolution, *p* is the radian pixel size, and *d* is the viewable distance in meters.

Figure 6. Camera platform for real-time terrain assessment

The processing power on-board the rover consists of a 333 MHz Pentium II processor housed in a CompactPCI chassis running the Linux Operating System. Resident on the computer are the image processing algorithms and the fuzzy computation engine used to calculate the translational and rotational speed commands sent to control the wheel motors. An external laptop computer, running Linux, is linked to the rover through an RF modem pair. The laptop allows the user to specify desired goal positions for the rover.

Camera	Cartesian (mm) x	y	Orientation
1L	-276	-64	-56°
1R	-64	276	-60°
2L	-200	200	2°
2R	200	200	2°
3L	64	276	60°
3R	276	-64	56°
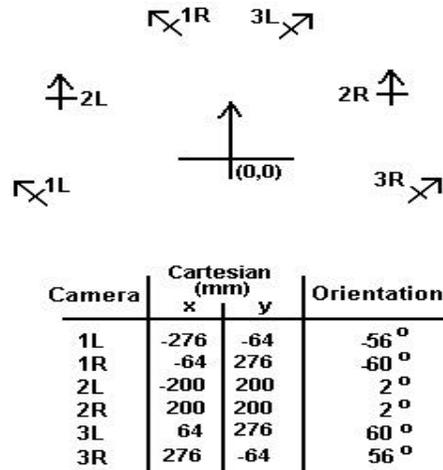
Figure 7. Camera positions and orientations

NAVIGATION EXPERIMENTS

Using this hardware platform, physical rover experiments are performed in the JPL Mars Yard to simulate planetary-like terrain conditions. The real-time terrain assessment algorithm involves using three pairs of stereo images representing a 180° field of view and processing terrain quality information at a distance of up to 5 meters in front of the vehicle. Figure 8 shows a typical panoramic image of the three stereo pairs with the left, front and right views of the panorama shown from left to right.

Figure 8. Image sets from three on-board stereo cameras

Each pair of stereo images is input into the slope and roughness image processing algorithms described above. Once the terrain characteristics are extracted, the outcome is used for evaluating the Traversability Index for each region. The processing time for the terrain assessment algorithm is less than 2 seconds CPU time. Figures 9-10 present two case studies validating the navigation capability of the rover. Tables III-IV show the calculated traversability parameters and the translational output values determined from the terrain-based navigation rules. As shown in Figure 9-10, the safest traversable region for the rover is chosen by the system for traversal.
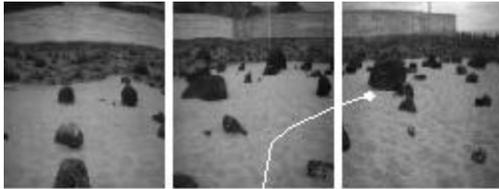
Figure 9. Case study one

	Left	Front	Right
Slope	LOW	LOW	LOW
Roughness	ROUGH	SMOOTH	ROUGH
Traversability	MED	HIGH	MED
Velocity	FAST		

Table III: Case Study One

Figure 10. Case study two

	Left	Front	Right
Slope	LOW	LOW	LOW
Roughness	ROUGH	ROUGH	ROUGH
Traversability	MED	MED	MED
Velocity	MODERATE		

Table IV: Case Study Two

CONCLUSIONS

This paper presents a real-time autonomous navigation system for a mobile robot operating on natural terrains. The implementation of the fuzzy logic methodology and on-board terrain assessment algorithm is shown to provide a natural framework for representing the physical characteristics of the terrain. Through experimentation, it is shown that the integration of fuzzy rules for terrain-traverse and goal-seeking behaviors allows the construction of an autonomous navigation strategy for a mobile robot that requires no *a priori* knowledge about the environment. Future research will be focused on

integrating a fuzzy-based real-time collision avoidance algorithm into the complete navigation strategy and performing several field testings.

ACKNOWLEDGMENTS

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