TRAVERSABILITY INDEX: A NEW CONCEPT FOR PLANETARY ROVERS

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Abstract

Traversability Index is introduced in this paper as a new and simple measure for traversability of natural terrains by mobile robots. This index is developed using the framework of fuzzy logic, and is expressed by linguistic fuzzy sets that quantify the suitability of the terrain for traversal based on its physical properties, such as slope and roughness. The Traversability Index is used for classifying natural terrains, and provides a simple means for incorporating the terrain quality data (out to about 10 meters) into the rover navigation strategy. A set of fuzzy navigation rules is developed using the Traversability Index to guide the rover toward the safest and the most traversable terrain. In addition, another set of fuzzy rules is developed to drive the rover from its initial position to a user-specified goal position. These two rule sets are integrated in a two-stage procedure for autonomous rover navigation without a priori knowledge about the environment. A computer simulation study is presented to demonstrate the capability of the rover to reach the goal safely while avoiding impassable terrains.

1 Introduction

Although considerable research has been conducted on mobile robots in recent years, the bulk of this research is focused on in-door robots operating in highly-structured, human-made environments. Typically, the environment consists of a flat, smooth, horizontal floor on which the robot moves. *Field* mobile robots, on the other hand, must traverse harsh *natural* terrains that are uneven, rough, and have slopes. These physical properties of the terrain add a new dimension to the complexity of the robot navigation problem. Rover navigation on Martian and Lunar surfaces has been an active area of research at JPL and CMU, respectively, [see, e.g., 1-2]. The photograph of the Martian terrain shown in Figure 1 indicates that each region of the terrain offers different traversability characteristics to the Sojourner rover in the Mars Pathfinder Mission.

In this paper, a new concept called *Traversability Index* is introduced for the first time for mobile robots (rovers) operating on natural terrains. This index is expressed by linguistic fuzzy sets that represent the suitability of the terrain for traverse based on its physical properties, such as slope and roughness. The index also gives a basis for classifying natural terrains according to their ease of traverse, ranging from "highly-impassable" to "highly-passable" terrains. Using the Traversability Index, a set of fuzzy navigation rules is developed to guide the rover toward the safest and the most traversable terrain. This rule set is integrated with fuzzy rules for goal seeking to obtain an autonomous navigation strategy for a mobile robot that requires no *a priori* knowledge about the environment.

The paper is structured as follows. In Section 2, the Traversability Index is defined using the fuzzy logic framework. A set of fuzzy navigation rules based on this index is presented in Section 3. Section 4 discusses fuzzy logic rules for the rover goal seeking. The integration of the terrain traversing and goal seeking fuzzy rule sets is described in Section 5. An illustrative example is presented in Section 6 for proof-of-concept and demonstration. The paper is concluded in Section 7 with a brief review and future plans.

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2 Traversability Index for Field Robots

This section establishes *Traversability Index* as a new and simple measure for traversability of natural terrains by mobile robots. This index is developed using the framework of fuzzy logic, which has been used extensively for navigation of in-door mobile robots operating in structured environments [see, e.g., 3-11]. The Traversability Index τ is expressed by linguistic fuzzy sets quantifying how traversable a particular terrain is for a given rover. Several options are available for defining the Traversability Index as a function of the terrain physical properties. In this paper, the Traversability Index τ is defined by fuzzy relations in terms of two physical variables: the terrain slope α and the terrain roughness β, where α and β are both expressed by linguistic fuzzy sets as described below.

2.1 Terrain Slope α

The terrain slope α can be measured by a stereo vision system mounted on the rover [1]. The slope α is represented by the four linguistic fuzzy sets { LOW, MEDIUM, HIGH, VERY HIGH }. The membership functions of these sets are shown in Figure 2a, where the abscissa α is the magnitude of the terrain slope and the ordinate $\mu(\alpha)$ is the degree-of-membership. Note that the slope can be either a positive quantity representing a mound or a hill, or a negative quantity representing a crater or a downward surface. Observe that precise measurement of the terrain slope is *not* needed using the fuzzy logic framework.

2.2 Terrain Roughness β

Several methods can be adopted to assess the terrain roughness β. For instance, the roughness β can be computed using a least-squares fitting algorithm based on the range map obtained by the on-board stereo vision system [1]. Alternatively, the terrain roughness β can be computed from two measurements supplied by the vision system: the rock sizes and the rock concentration (density) on the terrain. Let δ denote the "average" rock size ($\approx$ height $\times$ cross-sectional area) on the terrain. Then δ can be represented by the two linguistic fuzzy sets { SMALL, LARGE }. Similarly, the rock concentration on the terrain is denoted by ω, and is represented by the two linguistic fuzzy sets { LOW, HIGH }. Then, the terrain roughness β can be expressed in terms of the rock size δ and the rock concentration ω using a set of simple fuzzy relations. Let β be represented by the four linguistic fuzzy sets { SMOOTH, ROUGH, BUMPY, ROCKY }, where the membership functions are shown in Figure 2b. The dependence of β on δ and ω can then be expressed intuitively by a set of four simple fuzzy rules summarized in Table 1. Notice that precise measurements of the average rock size δ and the rock concentration ω are *not* needed, because of the multi-valued nature of the linguistic fuzzy sets used to describe them.

2.3 Traversability Index τ

The Traversability Index τ is defined by a set of fuzzy relations in terms of the slope α and the roughness β of the terrain. In the framework of fuzzy logic, the *Cartesian product* is used to represent fuzzy functional relations [12]. Let $A = \{A_1, A_2, A_3, A_4\}$ and $B = \{B_1, B_2, B_3, B_4\}$ represent, respectively, the fuzzy sets defined on the input variables α and β. The Cartesian product of these input fuzzy sets is the output fuzzy set $T = A \times B$ with the membership function defined by $\mu(\tau) = \mu(\alpha) * \mu(\beta)$, where $*$ denotes one form of the fuzzy set union ("and") operation and T is the fuzzy set of the output variable τ. The Traversability Index τ is represented by the four linguistic fuzzy sets $T =$ { POOR, LOW, MEDIUM, HIGH }, with the membership functions shown in Figure 2c. In the context of the Traversabilty Index τ, the Cartesian product functional relation can be represented by a set of sixteen simple fuzzy rules summarized in Table 2. Based on these rules, it is seen that the Traversability Index of the terrain τ is defined to be POOR when the terrain slope α is VERY HIGH or the terrain roughness β is ROCKY (see fourth row and column in Table 2). This implies that terrains with very high slope or with rocky surfaces are considered to be highly impassable and must be avoided. When these two extreme cases are excluded, the Traversability Index τ falls in the range of possible values spanned by the four fuzzy sets POOR through HIGH, depending on the slope and roughness of the terrain (see rows 1-3 and columns 1-3 in Table 2). Note that the Traversability Index varies with the size, drive mechanism, and rock climbing capability of the rover, and therefore the above definitions apply to the *particular* rover under consideration with the given mechanical design.

The fuzzy logic process for computation of the Traversability Index τ consists of the following stages. The terrain roughness β is first obtained by fuzzy inference from the on-board measurements of the terrain rock size and concentration δ and ω. The crisp values of the terrain slope α and the terrain roughness β are then passed through the "fuzzification" stage to find the degrees-of-membership in their corresponding fuzzy sets. This data is then used to evaluate the Traversability Index based on the fuzzy rules given in Table 2. This stage, which is referred to as "inference" in fuzzy logic, produces the activation levels or strengths of the rules that are "fired" using the max-min fuzzy inference method [12]. This information is then passed to the "defuzzification" stage where the crisp value of the Traversability Index τ is computed using the centroid defuzzification method [12]. Note that the fuzzy logic framework used for computation of τ only requires reasonable estimates of the terrain quality data α and β obtainable from inexpensive sensors that are expected to be imprecise. This method does *not* need expensive precision sensors that also require extensive processing of sensory data for precise interpretations.

2.4 Terrain Classification Based on τ

The Traversability Index provides a basis for classifying natural terrains according to their ease of traverse by the rover. Using the fuzzy linguistic description of the Traversability Index τ, different regions of the terrain can be classified into four categories based on their value of τ. The four linguistic fuzzy sets for τ can be interpreted as follows:

- POOR $\tau \rightarrow$ HIGHLY-IMPASSABLE TERRAIN.
- LOW $\tau \rightarrow$ IMPASSABLE TERRAIN.
- MEDIUM $\tau \rightarrow$ PASSABLE TERRAIN.
- HIGH $\tau \rightarrow$ HIGHLY-PASSABLE TERRAIN.

3 Navigation Rules Based on Traversability Index

In this section, the Traversability Index defined in Section 2 is used to develop simple rules for determination of the rover heading and speed on a planetary surface. In other words, the Traversability Index is used to navigate the rover toward the safest and the most traversable terrain. This index provides a simple means for incorporating the terrain quality data (out to about 10 meters) into the rover navigation strategy. The control variables of the rover are the translational speed v and the heading angle change $\Delta\theta$ per control cycle. We shall now discuss the fuzzy rules for determination of the rover heading change and the rover speed based on the Traversability Index.

3.1 Turn Rules

It is assumed that the rover can only move in the forward direction (i.e., reverse motion is not allowed). The terrain in front of the rover is partitioned into five regions, namely: front, front-right, front-left, right, and left of the rover at a distance up to r from the rover, where r defines the radius of the sensing envelope and is typically 10 meters [1]. The "front" refers to the region the rover is heading toward at present, "front-right" and "front-left" regions are sectors at $\pm 45°$ relative to the rover heading, and "right" and "left" regions are sectors between $\pm 45°$ and $\pm 90°$ relative to the heading. The terrain traversability data is assumed to be available for the five regions. Therefore, at any instant, five crisp Traversability Indices are computed for the five possible traversable regions described above, namely: τ_f, τ_{fr}, τ_{fl}, τ_r and τ_l. At this stage, the on-board software compares these five quantities and selects the one with the highest value τ_{max}, that is, the most traversable region is chosen. When the situation has a non-unique solution, i.e., there is more than one region with the highest τ, then the one which is closest to the front region is chosen so that unnecessary rotations are avoided. The five turn rules are as follows:

- IF $\tau_{max} = \tau_l$, THEN $\Delta\theta$ is HARD-LEFT.
- IF $\tau_{max} = \tau_{fl}$, THEN $\Delta\theta$ is LEFT.
- IF $\tau_{max} = \tau_f$, THEN $\Delta\theta$ is ON-COURSE.

- IF $\tau_{max} = \tau_{fr}$, THEN $\Delta\theta$ is RIGHT.
- IF $\tau_{max} = \tau_r$, THEN $\Delta\theta$ is HARD-RIGHT.

where { HARD-LEFT, LEFT, ON-COURSE, RIGHT, HARD-RIGHT } represent the five linguistic fuzzy sets of the rover heading change $\Delta\theta$, with the membership functions shown in Figure 3a.

3.2 Move Rules

Once the region to be traversed is chosen based on the relative values of τ, the rover speed v can be determined based on the value τ_{max} of the Traversability Index τ in the chosen region. This determination is formulated as a set of four simple fuzzy move rules as follows:

- IF τ_{max} is POOR, THEN v is STOP.
- IF τ_{max} is LOW, THEN v is SLOW.
- IF τ_{max} is MEDIUM, THEN v is MODERATE.
- IF τ_{max} is HIGH, THEN v is FAST.

where {STOP, SLOW, MODERATE, FAST } represent the four linguistic fuzzy sets associated with the rover speed v, with the membership functions shown in Figure 3b.

4 Fuzzy Rules for Goal Seeking

In this section, we present fuzzy rules for navigation of the rover from its current position to the desired goal position. Two sets of rules are developed for the rover speed v and the rover heading change $\Delta\theta$. The basic idea behind the navigation rules is that the rover tries to: (1) approach the goal with a speed proportional to the distance between the current position and the goal position, defined as the "position error" d, (2) rotate toward the goal position by nullifying the "heading error" ϕ, which is the angle by which the rover needs to turn to face the goal directly.

We shall now present the fuzzy navigation rules for goal seeking in the following subsections.

4.1 Turn Rules

The rover heading change $\Delta\theta$ depends on the heading error ϕ, where the angles are defined to be positive in the clockwise direction. The heading error ϕ has the linguistic fuzzy sets { GOAL-FAR LEFT, GOAL-LEFT, HEAD-ON, GOAL-RIGHT, GOAL-FAR RIGHT }, with the membership functions depicted in Figure 4a. The fuzzy rules for the rover turn are as follows:

- IF ϕ is GOAL-FAR LEFT, THEN $\Delta\theta$ is HARD-LEFT.
- IF ϕ is GOAL-LEFT, THEN $\Delta\theta$ is LEFT.
- IF ϕ is HEAD-ON, THEN $\Delta\theta$ is ON-COURSE.
- IF ϕ is GOAL-RIGHT, THEN $\Delta\theta$ is RIGHT.
- IF ϕ is GOAL-FAR RIGHT, THEN $\Delta\theta$ is HARD-RIGHT.

It is seen that the rover heading change $\Delta\theta$ is only a function of the heading error ϕ, and is independent of the rover speed v.

4.2 Move Rules

The rover speed v is generated by the position error d. The goal distance or position error d has the linguistic fuzzy sets { VERY NEAR, NEAR, FAR, VERY FAR }, with the membership functions depicted in Figure 4b. The fuzzy rules for the rover speed are as follows:

- IF d is VERY NEAR, THEN v is STOP.
- IF d is NEAR, THEN v is SLOW.
- IF d is FAR, THEN v is MODERATE.
- IF d is VERY FAR, THEN v is FAST.

It is seen that the rover speed v is only a function of the goal distance d, and is independent of the heading error ϕ.

5 Integration of Traverse and Seek Behaviors

In the preceding two sections, fuzzy rule sets are given for the two *independent* behaviors of terrain traversing and goal seeking. The rule set for each behavior is concerned solely with achieving its particular objectives, disregarding the constraints imposed by the other behavior. In this section, we discuss the integration of these two behaviors to obtain an autonomous navigation strategy for the rover. A two-stage procedure is proposed for autonomous rover navigation without *a priori* knowledge about the environment. In the first stage, the traverse-terrain and seek-goal rule sets make their individual, independent recommendations for rover speed and heading change commands. In the second stage, these recommendations are integrated by using appropriate weighting factors to generate the combined, coordinated recommendation for the rover navigation based on the rover status.

Consider the rover navigation procedure shown in the block diagram of Figure 5. Each of the two behaviors, traverse-terrain and seek-goal, generates a set of independent recommendations for v and $\Delta\theta$ based on its own objectives. These sets of recommendations $\{v^t\}, \{\Delta\theta^t\}$ and $\{v^s\}, \{\Delta\theta^s\}$ are then "weighted" by the crisp weighting factors t_w and s_w assigned to the outputs of the traverse-terrain and seek-goal behaviors, respectively. In other words, the final recommendations $\overline{v}$ and $\overline{\Delta\theta}$ result from defuzzification of the weighted aggregated outputs of the traverse-terrain and seek-goal rule sets. The weighting factors t_w and s_w represent the strengths by which the traverse-terrain and seek-goal recommendations are taken into account. These factors are represented by the linguistic fuzzy sets {NOMINAL, HIGH }, whose triangular membership functions have the central values of 1 and 10, respectively. Within this context, the traverse and seek weighting factors are assumed to have the fuzzy NOMINAL value except in the following extreme cases:

- IF τ is POOR OR τ is LOW, THEN t_w is HIGH.
- IF d is VERY NEAR, THEN s_w is HIGH.

The first rule implies that when the terrain is not easily passable by the rover, the recommendation of the traverse-terrain rule set is assigned a HIGH weighting factor with the central value 10 relative to the seek-goal recommendation which has the NOMINAL weighting factor with the central value 1. The second rule suggests that when the goal position is almost reached, the seek-goal recommendation takes on the HIGH weighting factor relative to the NOMINAL weighting factor for the traverse-terrain recommendation. Excluding these two extreme cases, the traverse-terrain and seek-goal recommendations for v and $\Delta\theta$ are combined using equal weightings of unity to obtain the final recommendations for the rover speed and heading change $\overline{v}$ and $\overline{\Delta\theta}$ that are passed to the rover for execution.

6 Illustrative Example

In this section, a computer graphical simulation study is presented to demonstrate fuzzy logic-based rover navigation using the traverse-terrain and seek-goal rule sets developed in this paper. The simulations are performed using the Rover Graphical Simulator (RGS) developed at JPL. This simulator is written in Java and is platform-independent, running on both PC and Unix machines. The RGS provides an essential tool for visualization of the rover reasoning and decision-making capabilities using the fuzzy logic navigation rule sets. It depicts a terrain composed of regions with different grades of traversability, together with the initial and goal rover positions. The rule sets for the two behaviors, namely, traverse-terrain and seek-goal, are integrated in the RGS. A simple Graphical User Interface (GUI) is provided to issue rover motion commands and display the rover movements graphically under the fuzzy navigation rules.

In this study, there are three impassable regions between the initial and the goal positions of the rover as depicted by dark circles in Figure 6. The rover is required to drive to the goal position while avoiding the three regions. These regions are a crater with POOR Traversability Index, a high-slope region with POOR Traversability Index, and an area of high rock density with LOW Traversability Index. The remaining regions of the terrain have HIGH Traversability Index. The path traversed by the rover under the fuzzy traverse-terrain and seek-goal rule sets is shown by the dotted line in Figure 6. It is seen that the test is successfully completed with the rover reaching the goal safely while avoiding the three impassable terrains.

7 Conclusions

The new concept of Traversability Index is introduced in this paper for mobile robots operating on natural terrains. Fuzzy logic framework is used to define the Traversability Index in terms of the physical properties of the terrain, such as slope and roughness. This index is used to classify natural terrains according to their suitability for traverse by the rover. A set of fuzzy navigation rules based on this concept is developed to guide the robot toward the most traversable terrain. These rules are then integrated with another set of fuzzy rules for goal seeking to obtain an autonomous navigation strategy for a field rover.

Fuzzy logic provides a natural framework for formulating and expressing the attributes of the human navigation expertise and for emulating this expertise for field mobile robots. The use of linguistic fuzzy sets is simple, intuitive, and akin to the human reasoning and decision-making processes. A novel feature of the proposed approach is the utilization of the *regional* traversability information obtained from the terrain data for rover navigation. This information augments the *local* information obtained from en-route obstacles to provide a comprehensive approach for autonomous rover navigation that requires no *a priori* knowledge about the environment. Future research is focused on implementation and verification of the proposed approach on a commercial mobile robot designed for out-door operations.

8 Acknowledgments

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9 References

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Figure 1. Photograph of the Martian terrain

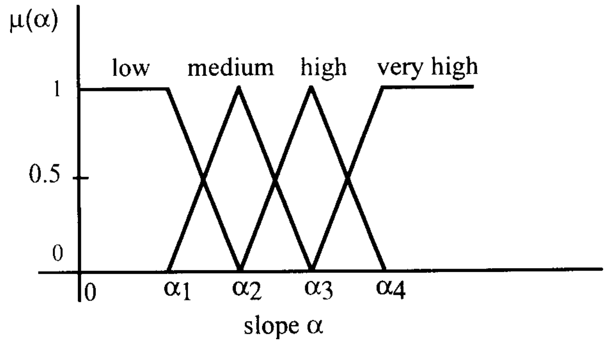

Figure 2a. Membership functions for terrain slope α

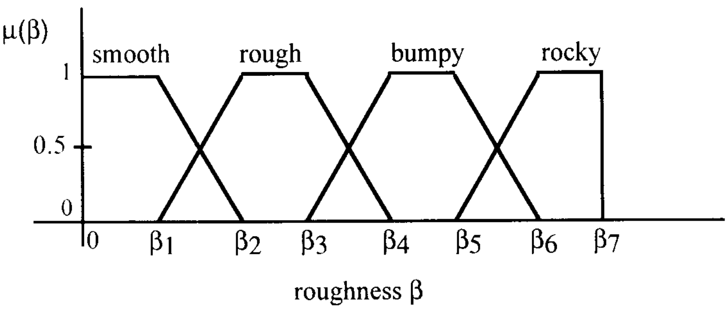

Figure 2b. Membership functions for terrain roughness β

rock size δ \ rock concentration ω	low	high
small	smooth	rough
large	bumpy	rocky

Table 1. Rule set for terrain roughness β

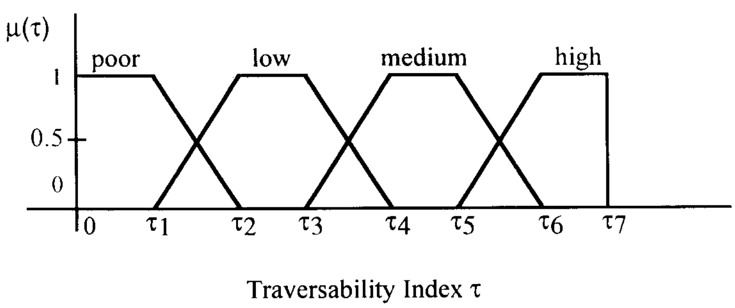

Figure 2c. Membership functions for Traversability Index τ

terrain slope α \ terrain roughness β	smooth	rough	bumpy	rocky
low	high	medium	low	poor
medium	medium	medium	low	poor
high	low	low	poor	poor
very high	poor	poor	poor	poor

Table 2. Rule set for Traversability Index τ

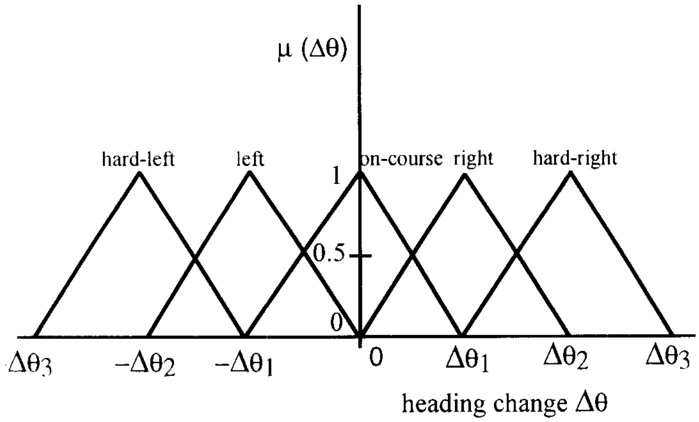

Figure 3a. Membership functions for heading change $\Delta\theta$

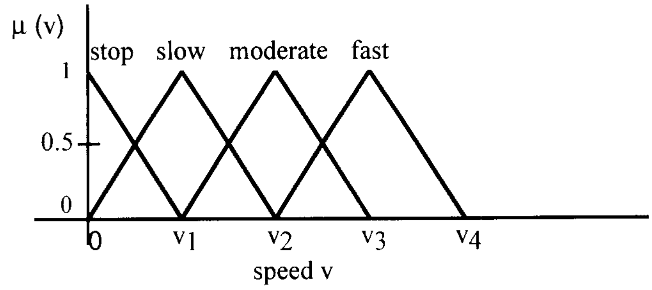

Figure 3b. Membership functions for speed v

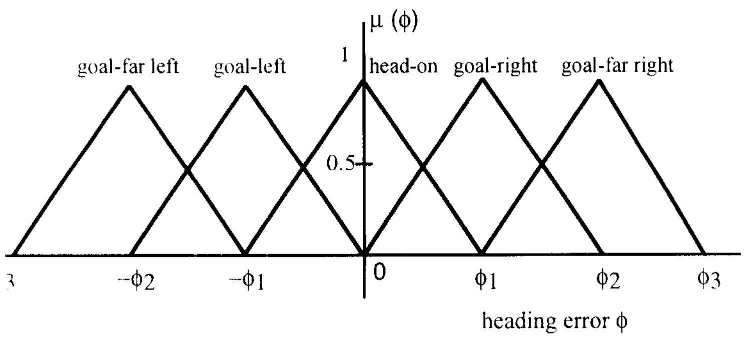

Figure 4a. Membership functions for heading error ϕ

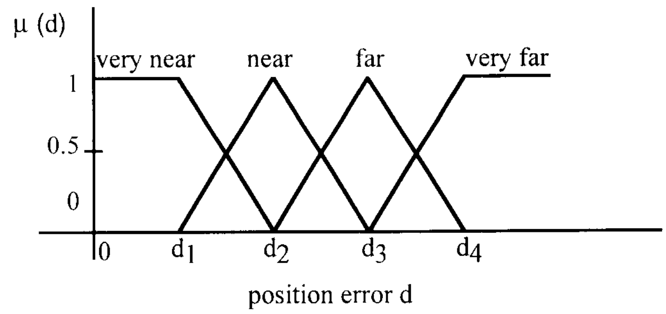

Figure 4b. Membership functions for position error d

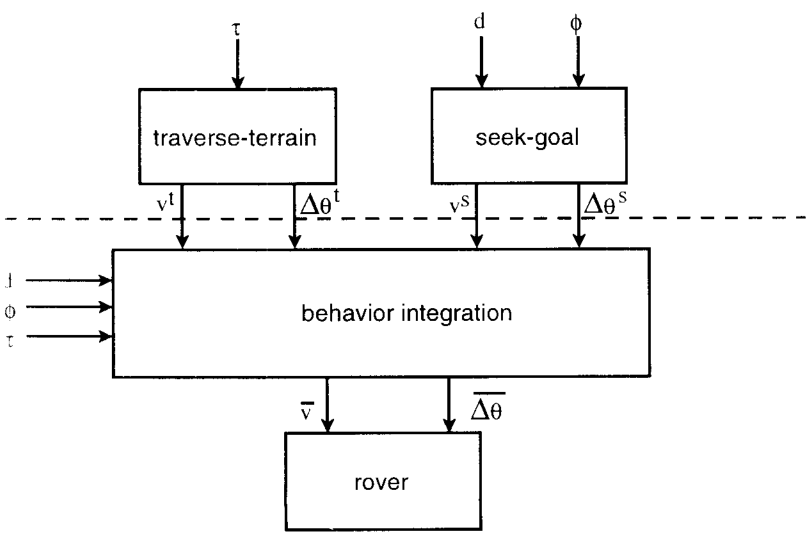

Figure 5. Two-stage rover navigation procedure

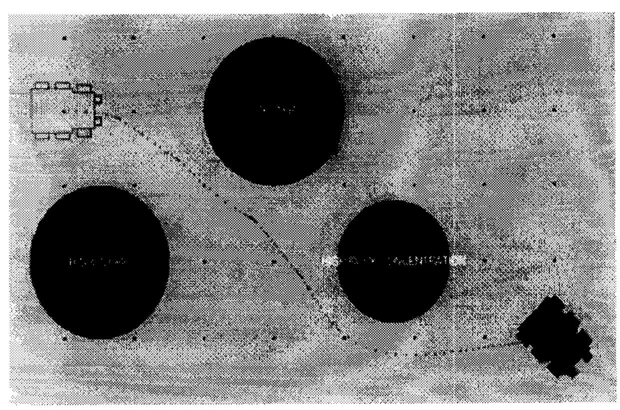

Figure 6. Simulation of the fuzzy navigation rules