# Fuzzy Behavior-based Navigation for Planetary Microrovers

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**Abstract**

Adaptive behavioral capabilities are necessary for robust rover navigation in unstructured and partially-mapped environments. A control approach is described which exploits the approximate reasoning capability of fuzzy logic to produce adaptive motion behavior. In particular, a behavior-based architecture for hierarchical fuzzy control of microrovers is presented. Its structure is described, as well as mechanisms of control decision-making which give rise to adaptive behavior. Control decisions for local navigation result from a consensus of recommendations offered only by behaviors that are applicable to current situations. Simulation predicts the navigation performance on a microrover in simplified Mars-analog terrain.

## 1 Introduction

During the years between 1996 and 2005, NASA will embark on several missions to explore planet Mars. As a part of these exploration initiatives NASA plans to make use of microrovers, which are small mobile robots with mobility characteristics that are sufficient for traversing rough and natural terrain. The first microrover, named *Sojourner* [1], was launched aboard the Mars Pathfinder spacecraft in December of 1996 and is scheduled to arrive on Mars in July of 1997. This planetary rover is part of the payload of the spacecraft's lander which also carries a stereo imaging system and various science instruments. *Sojourner* will demonstrate the viability of exploring planetary surfaces using mobile robot technology; its mission will be limited to minimal surface exploration. The focus of ongoing research to develop enabling technology for subsequent microrover deployments is increased mobility and increased autonomy [2, 3]. In this paper, we focus on the latter.

Robustness and adaptability are essential for increasing microrover navigation capabilities beyond those of *Sojourner*. Realization of robust behavior requires that uncertainty be accommodated by the rover control system. Fuzzy logic is particularly well-suited for implementing such controllers due to its capabilities of inference and approximate reasoning under uncertainty. In order to achieve autonomy, microrovers must be capable of achieving multiple goals whose priorities may change with time. Thus, controllers should be designed to realize a number of task-achieving behaviors that can be integrated to achieve different control objectives. State-of-the-art microrover navigation employs simple behavior control strategies that are based on finite state machines [2, 4]. A different approach which exploits the approximate reasoning facility of fuzzy logic is presented here [5]. It is a hierarchical behavior-based control architecture which enables distribution of intelligence amongst special-purpose *fuzzy-behaviors*. This structure is motivated by the hierarchical nature of behavior as hypothesized in ethological models.[1] A fuzzy coordination scheme is

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[1] Models which describe animal behavior patterns.

also described that employs weighted decision-making based on contextual behavior activation. Performance is demonstrated by simulated microrover navigation example in simplified Mars-analog terrain. Interesting aspects of the decision-making process which give rise to adaptive behavior are highlighted.

# 2 Hierarchical Fuzzy-Behavior Control

The behavior control paradigm has grown out of an amalgamation of ideas from ethology, control theory and artificial intelligence [6, 7]. Motion control is decomposed into a set of special-purpose behaviors that achieve distinct tasks when subject to particular stimuli. Clever coordination of individual behaviors results in emergence of more intelligent behavior suitable for dealing with complex situations. Most behavior controllers have been based on crisp (non-fuzzy) data processing and binary logic-based reasoning [4, 7]. The incorporation of fuzzy logic into the framework of behavior control has been proposed to enhance multiple behavior coordination and conflict resolution [8]. Fuzzy behavior control has also been proposed for autonomous planetary rover navigation in Lunar [9] and Mars [5, 10] missions. Such controllers provide robustness to perturbations, design simplicity, and efficiency in dealing with continuous variables.

In contrast to their crisp counterparts, fuzzy-behaviors are synthesized as fuzzy rule-bases, i.e. collections of a finite set of fuzzy if-then rules. Each behavior is encoded with a distinct control policy governed by fuzzy inference. If $X$ and $Y$ are input and output universes of discourse of a behavior with a rule-base of size $n$, the usual fuzzy if-then rule takes the following form

$$IF\ x\ is\ \tilde{A}_i\ THEN\ y\ is\ \tilde{B}_i \tag{1}$$

where $x$ and $y$ represent input and output fuzzy linguistic variables, respectively, and $\tilde{A}_i$ and $\tilde{B}_i$ $(i = 1...n)$ are fuzzy subsets representing linguistic values of $x$ and $y$. Typically, $x$ refers to sensory data and $y$ to actuator control signals. The antecedent consisting of the proposition "$x$ is $\tilde{A}_i$" could be replaced by a conjunction of similar propositions; the same holds for the consequent "$y$ is $\tilde{B}_i$".

## 2.1 Microrover Behavior Hierarchy

In the proposed architecture, a collection of *primitive behaviors* resides at the lowest level which we refer to as the primitive level. These are simple, self-contained behaviors that serve a single purpose by operating in a reactive or reflexive fashion. They perform nonlinear mappings from different subsets of the rover's sensor suite to (typically, but not necessarily) common actuators. Each exists in a state of solipsism, and alone, would be insufficient for autonomous navigation tasks. Primitive behaviors are building blocks for more intelligent *composite behaviors*. They can be combined synergistically to produce behavior(s) suitable for accomplishing goal-directed missions.

Autonomous microrovers must be capable of point-to-point navigation in the presence of varying obstacle (rocks, boulders, dense vegetation, etc.) distributions, surface characteristics, and hazards. Often the task is facilitated by knowledge of a series of waypoints, furnished by humans, which lead to designated goals. In some cases, such as exploration of the surface of Mars [1, 11], this supervised autonomous control must be achieved without the luxury of continuous remote communication between the mission base station and the microrover.[2] Considering these and other constraints associated with planetary rover navigation, suitable behavior hierarchies similar to the hypothetical one shown in Figure 1 could be constructed. In this figure the behavioral functions of `goal-seek`, `route-follow`, and `localize` are decomposed into a suite of primitive behaviors. In Mars exploration mission scenarios [1, 3], microrover position, and all other coordinates of interest, are typically referenced relative to a coordinate frame located at the lander. Thus, any subsequent mention of coordinates or locations refers to the lander coordinate frame of reference. The composite behavior, `goal-seek`, is responsible for collision-free navigation to a goal location. `Route-follow`

[2]Time delays between Earth and Mars can be anywhere between 6 and 41 minutes.

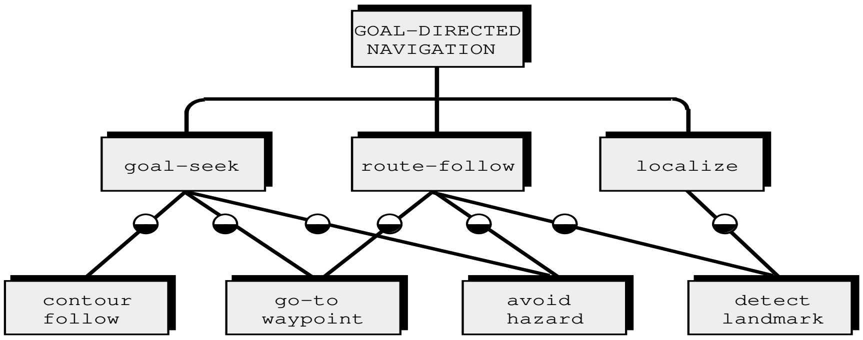


Figure 1: Hypothetical behavior hierarchy for microrover navigation.

is responsible for navigation via a set of waypoints that lead to a goal. Self-localization via dead-reckoning and, perhaps, reference to distinguishable landmarks is the responsibility of `localize`.

The behavior hierarchy shown implies that goal-directed navigation can be decomposed as a behavioral function of these composite behaviors. They can be further decomposed into the primitive behaviors shown, with dependencies indicated by the adjoining lines. Examples of terrain features which could be considered hazards for microrover navigation include rocks, pits, and excessive slopes. In this paper, we will be primarily concerned with rocks. As its name implies, the purpose of the `avoid-hazard` behavior is to avoid collision with rocks. Later we specify a minimum rock diameter for rocks which are considered hazards. The `go-to-waypoint` behavior will direct the microrover to traverse a straight line trajectory to a specified waypoint or goal. When close to obstacle (rock) boundaries, `contour-follow` maintains the microrover's lateral distance from the obstacle while cirumnavigating it. Finally, `detect-landmark` guides the microrover in search of distinct features which represent landmarks that facilitate self-localization. Interconnecting circles between composite behaviors and the primitive level represent weights and activation thresholds of associated primitive behaviors. Fluctuations in these weights are at the root of the intelligent coordination of primitive behaviors. The hierarchy facilitates decomposition of complex problems as well as run-time efficiency by avoiding the need to evaluate rules from behaviors that do not apply.

Note that decomposition of behavior for a given planetary rover is not unique. Consequently, suitable behavior repertoires and associated hierarchical arrangements are arrived at following a subjective analysis of the system and the task environment. For an actual mission, the design of behaviors at the primitive level would be tailored to the navigation task and an environment with characteristics of natural terrain. The total number, and individual purpose, of fuzzy-behaviors in a given behavior hierarchy is indicative of the problem complexity and can be conveniently modified as required.

# 3 Coordinating Fuzzy-behavior Interactions

Complex interactions in the form of behavioral cooperation or competition occur when more than one primitive behavior is active. These forms of behavior are not perfectly distinct; they are extremes along a continuum [12]. Coordination is achieved by weighted decision-making and behavior modulation embodied in a concept called the *degree of applicability* (DOA). The DOA is a measure of the instantaneous level of activation of a behavior and can be thought of in ethological terms as a motivational tendency of the behavior. Fuzzy rules of composite behaviors are formulated such that the DOA, $\alpha_j \in [0,1]$, of primitive behavior $j$ is specified in the consequent of *applicability rules* of the form

$$IF\ x\ is\ \tilde{A}_i\ THEN\ \alpha_j\ is\ \tilde{D}_i \tag{2}$$

where $\tilde{A}_i$ is defined as in (1). $\tilde{D}_i$ is a fuzzy set specifying the linguistic value (e.g. "*high*") of $\alpha_j$ for the situation prevailing during the current control cycle. This feature allows certain microrover behaviors to influence the overall behavior to a greater or lesser degree depending on the current situation. It serves as a form of motivational adaptation since it causes the control policy to dynamically change in response to goals, sensory input, and internal state. Thus, composite behaviors are meta-rule-bases that provide a form of the ethological concepts of inhibition and dominance. Behaviors with maximal applicability ($\alpha_{max} \leq 1$) can be said to dominate, while behaviors with partial applicability ($0 < \alpha < \alpha_{max}$) can be said to be inhibited. These mechanisms allow exhibition of behavioral responses throughout the continuum. This is in contrast to crisp behavior selection which typically employs fixed priorities that allow only one activity to influence the rover's behavior during a given control cycle [4, 7]. The coordination scheme includes behavior selection as a special case when the DOA of a primitive behavior is nonzero and above its activation threshold, while others are zero or below threshold. When this occurs, the total number of rules to be consulted on a given control cycle is reduced. In fact, the number of rules consulted during each control cycle varies dynamically as governed by the DOAs and thresholds of the behaviors involved.

Fuzzy rules of each applicable primitive behavior are processed yielding respective output fuzzy sets. Each fuzzy behavior output is weighted (multiplied) by its corresponding DOA, thus effecting its activation to the level prescribed by the composite behavior. The resulting fuzzy sets are then aggregated and defuzzified to yield a crisp output that is representative of the intended coordination. Since control recommendations from each applicable behavior are considered in the final decision, the resultant control action can be thought of as a consensus of recommendations offered by multiple experts.

# 4 Microrover Navigation Example

In order to demonstrate fundamental operational aspects of the controller we consider only the composite behavior — `route-follow`. As illustrated in Figure 1, its effect arises from synergistic interaction between several primitive behaviors. In the following example, `avoid-hazard` and `go-to-waypoint` are used. Recall that these behaviors are only capable of exhibiting their particular primitive roles. When more behaviors are involved, the approach proceeds in a straightforward manner by appending additional DOAs and any necessary antecedents to applicability rules accordingly. The controller's performance is predicted by simulated microrover navigation in simplified Mars-analog terrain. That is, navigation through a region with a realistic rock distribution is considered, but the terrain is assumed to be two-dimensional. This is an over-simplification of actual microrover mission scenarios in which complex motions in the third dimension occur quite frequently. However, the two-dimensional simplification of Mars-analog terrain still allows us to test the proposed navigation approach in environments densely cluttered by irregularly-shaped obstacles (rocks). Until now, it has only been verified for navigation tasks in indoor office-like environments [5].

The simulated microrover is loosely modeled after *Sojourner*. As shown in Figure 2 its chassis is six-wheeled, with neither axles nor a suspension. It uses a passive rocker bogey mechanism designed to enable climbing over vertical obstacles of 1.5 wheel diameters in height. The $13cm$ diameter wheels are driven by six drive motors; one steering motor is used to independently steer each of the four corner wheels [11]. The steering capability allows for rotating in place. The microrover measures $65cm$ in length, $48cm$ in width and $30cm$ high; its mass is 11 kilograms. Primary navigation sensing consists of light-stripe triangulation (to determine distances to abstacles), turn rate sensing and dead-reckoning (odometry) using wheel encoders. We have simulated the obstacle distance sensing covering an area approximately 1 meter in front of the vehicle, and we have assumed ideal dead-reckoning. Turn rate information was not used. The simulated Martian surface is based on a model of rock size and frequency distributions derived from Viking mission data [13]. The model is know as Moore's model and we have used it here to generate a rock distribution over a $10m$x$10m$ region which replicates the Mars nominal terrain type [13]. The initial state, $(x\ y\ \theta)^T$, of the microrover is $(8.25\ 5.25\ -\frac{\pi}{2})^T$. Its task is to navigate to a goal at $(1.75, 6.0)$ via the following waypoints

$$(7.0, 5.0) \rightarrow (4.0, 6.25) \rightarrow (2.0, 7.0).$$

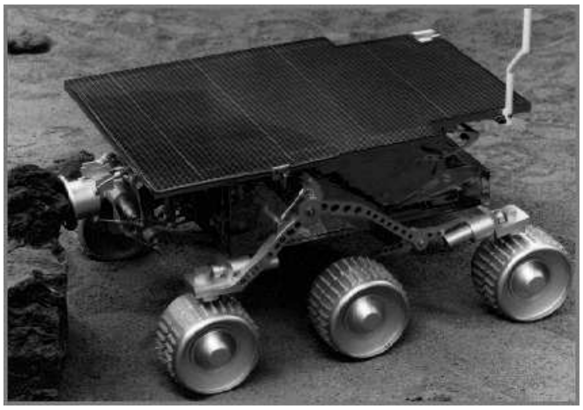

Figure 2: *Sojourner*: the Mars Pathfinder Microrover.

The resulting route is shown in the left half of Figure 3 where the oddly-shaped icons represent rocks with diameters of $20cm$, $40cm$ and $60cm$. Rocks with diameters less than $15cm$ are not considered to be obstacles. The microrover controlled by the fuzzy-behavior hierarchy successfully reaches the goal location via the specified waypoints. In the right half of the figure, the behavioral interaction during the run is shown as a time history of the DOAs of each primitive behavior. The interaction dynamics shows evidence of competition (overlapping oscillations) and cooperation with varying levels of dominance throughout the task. Initially, `avoid-hazard` has the dominant influence over the microrover. It competes with `go-to-waypoint` which dominates as each waypoint is approached. The applicabilities vary continuously reflecting levels of activation recommended by the behavior control system. The individual primitive behaviors are dynamically modulated to produce an overall behavior that accomplishes the navigation objective.

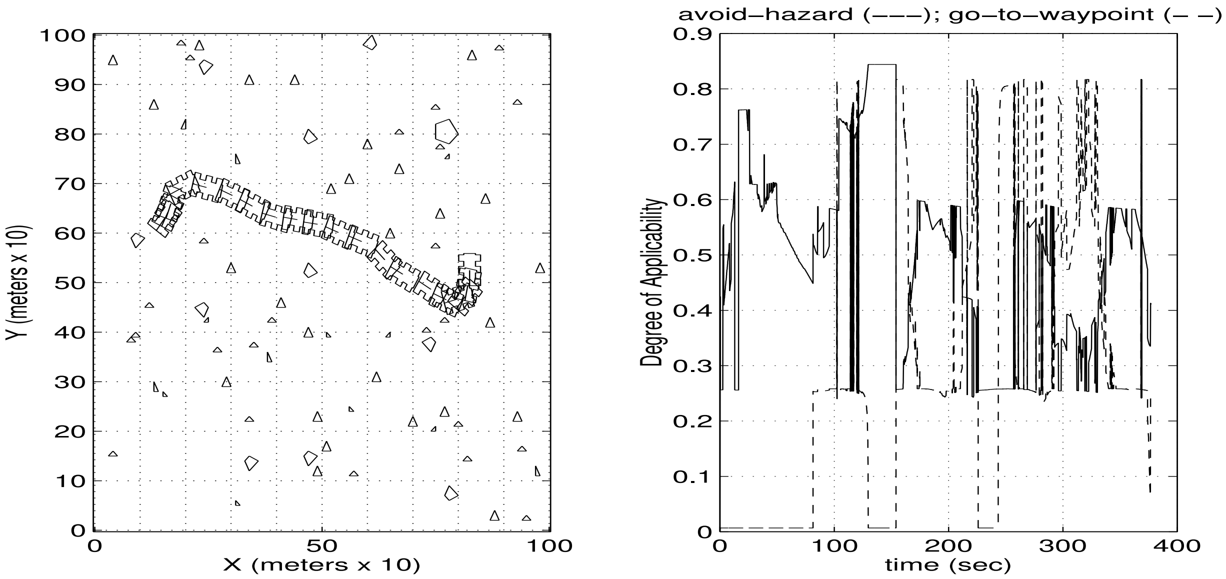


Figure 3: Microrover path and behavior modulation during route-following in Mars nominal terrain.

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## 5 Conclusion

The hierarchy of fuzzy-behaviors provides an efficient approach to controlling mobile vehicles. Its practical utility lies in the decomposition of overall behavior into sub-behaviors that are activated only when applicable. The modularity and flexibility of the approach, coupled with its mechanisms for weighted decision-making, makes it a suitable framework for modeling and controlling situated adaptation in autonomous microrovers. Here, simulation has been used to predict the performance of the approach when applied to microrover navigation in simplified Mars-analog terrain. Successful navigation runs dictate that the approach has potential for applications involving local navigation in densely cluttered, unstructured environments. Future extensions of this work will address three-dimensional simulation in more realistic terrain, and actual experiments pending procurement of a suitable microrover prototype.

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