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Robot navigation in very cluttered environments by preference-based fuzzy behaviors☆

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Abstract

One of the key challenges in application of Autonomous Ground Vehicles (AGVs) is navigation in environments that are densely cluttered with obstacles. The control task becomes more complex when the configuration of obstacles is not known a priori. The most popular control methods for such systems are based on reactive local navigation schemes that tightly couple the robot actions to the sensor information. Because of the environmental uncertainties, fuzzy behavior systems have been proposed. The most difficult problem in applying fuzzy-reactive-behavior-based navigation control systems is that of arbitrating or fusing the reactions of the individual behaviors, which is addressed here by the use of preference logic. This paper presents the design of a preference-based fuzzy behavior system for navigation control of robotic vehicles using the multivalued logic framework. As shown in simulation and experimental results, the proposed method allows the robot to smoothly and effectively navigate through cluttered environments such as dense forests. Experimental comparisons with the vector field histogram method (VFH) show that the proposed method usually produces smoother albeit longer paths to the goal.
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1. Introduction

Safe maneuvering of Autonomous Ground Vehicles (AGVs) in unstructured complex environments, densely cluttered with obstacles is still a major challenge in goal-directed robotic vehicle applications. Navigation through a forest, which attracts special interest from the military community due to the lack of stealth and concealment found in open environments, is typical of such challenges. This navigation problem is a multiobjective control problem that seeks to ensure that the robot not only reaches its goal without hitting obstacles, but also does so at safe speeds that ensure stability. The problem is particularly difficult because some of the navigational objectives may be in opposition to one another.

It is important that algorithms for navigation control in cluttered environments not be too computationally expensive as this would result in a sluggish response. It has been acknowledged that the traditional Plan-Sense-Model-Act approaches are not effective in such environments; instead, local navigation strategies that tightly couple the sensor information to the control actions must be used for the robot to successfully achieve its mission [27]. The control complexity is overcome by decomposing the navigation control problem into more simple and well-defined subproblems that can be controlled independently and in parallel. These subproblems and their controllers are known as reactive behaviors, and this approach is known as behavior robotics [3]. It has attracted the interests of many roboticists and has even been used in industrial process control applications [15].

Since its introduction in [5] behavior robotics has grown quickly resulting in the development of reactive fuzzy behavior

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methods that use fuzzy logic controllers, which can handle uncertainty in the robot information [1,10,13,14,19,22,30]. Fuzzy logic also allows a continuum of control variables such as heading angles and speeds to be considered, as opposed to the discrete numbers used in crisp behaviors. In addition, it allows the navigation algorithm to be programmed using linguistic terms, which is the way a designer naturally thinks. Probably, the greatest strength of behavior-based fuzzy approaches is that they operate on and reason with uncertain perception-based information, which makes them suitable even for difficult environments such as unknown terrains as shown in [26].

The concept of behavior control was initially seen as a special form of decentralized switching control in which each behavior is fully autonomous, and when allowed, can control the robot on its own without regard to other behaviors. Under what we will call the standard behavior paradigm, each behavior triggers a single control command that best meets the control responsibilities specific to that behavior. Hence, the behaviors are essentially competing. This ‘switched parallel’ structure works fairly well when the switching is relatively rare, but the performance of the robot becomes very poor if the behavior switching frequency becomes high, which can lead the robot to be indecisive [28]. If used in cluttered environments, where behavior switching is likely to be high, such an approach is also likely to fail.

Over time, there have been concerted efforts to make behaviors run cooperatively so that the overall robot reaction is generally an amalgamation of the commands from the individual behaviors through some form of command fusion [1,19,30,23,11]. However, most of these efforts have been based on developing fuzzy versions of the standard behavior structure in which each behavior chooses one action out of the possible actions, in this case a fuzzy action. These structures were found to have performance problems [18] especially since they treat behaviors as fully autonomous, which tends to cause the robot to be indecisive when the behaviors have mutually exclusive interests with nearly equal importance. This observation led to the introduction of what we will collectively refer to as preference-based behavior systems. The first of these were voting architectures like the DAMN architecture [18,21], where behaviors expressed their preference for or against a possible action through a voting system. The method of [18,21] was implemented using fuzzy logic in [31]. Independently Saffiotti et al. implemented a similar system using desirability functions and preference logic [24]. This early work was later generalized into the multivalued logic approach [23].

The primary contribution of this paper is the development and implementation of preference-based fuzzy behaviors to navigation of an AGV in very cluttered environments. An important and novel step in this process is the division of the laser range finder data into nine overlapping sensor regions (see Fig. 16). However, the behavioral architecture clearly builds upon the pioneering work of [31,23]. In fact, the actual methodology is very similar in form to that of [31]. However, one difference is that [31] employed the *three* command alternatives (left-forward, forward and right-forward) and the *two* degrees of fuzzy preference (acceptable and non-acceptable), while for smooth motion in very cluttered environments, this research actually employed the *five* command alternatives of Fig. 5 and the *four* degrees of fuzzy preference illustrated in Fig. 4. In addition, the early work of [31] lacked any experimental verification.

The later work of [23] provides a general formulation for an arbitrary number of command alternatives and degrees of fuzzy preferences. However, it employs a substantially different and more complex command fusion block. In particular, in [23] a *context-dependent blending* method, which is actually a fuzzy-logic-based weighting and blending mechanism, was first used to weight each behavior. The behaviors were further blended using *conjunctive combination*. However, the weights are highly dependent on the specific context and need to be chosen very carefully. In this research the much simpler fusion method of [31] is applied. The preference of each command alternative is the minimum preference from all the behaviors. This fusion works very well even when behaviors are conflicting.

An early algorithm for navigation in very cluttered environments, similar to the one presented here, was proposed in [25] without any experimental validation. Experimental results with the system of [25] demonstrated the need to redesign the behaviors proposed therein to make them behave more realistically and have greater computational efficiency. The practical implementation of this system on a Pioneer 2 robot equipped with a SICK laser range finder is described thoroughly and the resulting performance is also discussed in sufficient detail to show the capabilities of this algorithm.

The paper is organized as follows: Section 2 discusses the general structures of standard and preference-based systems and points out their differences. Section 3 presents the detailed structure of the proposed system. Simulation results that compare the performance of the proposed system with a navigation control system that uses standard behaviors are presented in Section 4. Section 5 shows the experimental results and the comparisons to the Vector Field Histogram method [4]. Concluding remarks are given in Section 6.

2. Standard and preference-based fuzzy behavior control structures

This section describes the general structures of standard and preference-based fuzzy behavior control systems. These structures can apply to a variety of control applications.

2.1. Standard structure for fuzzy behavior systems

A standard structure consists of a finite set of distributed independent fuzzy behaviors and a system of arbitration or command fusion. Each behavior is a fuzzy logic control system that responds to its stimuli by issuing a single command that is transmitted for command fusion. Fig. 1 shows the basic structure of these systems, where each of the behaviors use the environmental information to determine the control command that satisfies its particular objective, e.g., obstacle avoidance, path following, goal seeking, etc. The behaviors determine the appropriate control commands through rules of the form