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Fuzzy Logic and Behavior Control Strategy for Autonomous Mobile Robot Mapping

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Abstract -- *In support of research efforts to develop reactive mobile robots capable of autonomous navigation, we are concentrating on providing human reasoning capabilities as a resource for intelligence and integrating the world mapping and navigation tasks. The underlying philosophy is that an autonomous mobile robot should be able to make a map of its environment as it navigates through that environment. Fuzzy logic control and behavior-based navigation are proposed as means to implement this philosophy. Fuzzy logic provides the approximate reasoning necessary for handling the uncertainty inherent in mobile robot navigation. By decomposing the problem into simpler tasks we can develop mobile robots that exhibit a sufficient level of intelligence for performing navigation and mapping. In this paper, we discuss a strategy for incorporating fuzzy reasoning into the framework of reactive behavior control systems for autonomous mapping.*

1. Introduction

An aim of intelligent robotics research is to develop mobile robots capable of navigating autonomously in unstructured and/or unexplored environments. The practicality of such a robot is a function of its ability to utilize a map to locate itself and its goals as it navigates throughout. In some situations a map may be available a priori in which case goal locations on the map are specified and path planning algorithms are employed to direct the robot's motion while avoiding known (mapped) obstacles. A more desirable, and more challenging situation is for the robot to be able to generate and maintain its map autonomously.

The development of mobile robots capable of autonomous mapping and navigation requires intelligent control strategies that can handle the uncertainties presented by the real world. At the same time, real-time performance and relatively low computation must be maintained. Traditional approaches to mobile robot navigation have dealt with these requirements with the use of computationally intensive planning algorithms and explicit pre-determined world models [1]. The resulting systems exhibited robust behavior but at the great expense of real-time performance. In addition, the need for significant amounts of memory and processing power to store and maintain world models precluded the use of smaller (lightweight) computing systems. As pointed out in [2], this is not necessarily a drawback for fixed-base manipulators but it can be a problem for mobile robots for which computational resources must be carried onboard. These issues are of particular importance for mobile robots intended for use in space [3, 4].

We contend that the theory of fuzzy logic can be applied to alleviate some of the difficulties alluded to above. A fuzzy logic based system has the advantage that it allows the intuitive nature of collision-free navigation to be easily modeled using linguistic terminology. The computational demand of fuzzy inference systems is considerably lighter than that of traditional methods. The use of reactive fuzzy control systems permits intelligent decisions to be made in real-time, thus allowing for uninterrupted robot motion. In intelligent systems, the reactive control strategy dictates faster control cycles than more conventional systems since sensors are sampled at a higher rate. Moreover, accurate (expensive) sensors and detailed models of the environment are not absolutely necessary [5]. The successful management of uncertain and/or unmodeled data is a proven attribute of fuzzy logic based inference engines.

Furthermore, it has been suggested [6] that a reactive, behavior-based control system can reduce the computational requirements of traditional systems and still produce robust autonomous performance. Recent micro-rover rough terrain navigation work [7] is an excellent example of this. Behavior control, which makes reactive control possible, involves decomposing the motion control system into a set of special-purpose routines (behaviors) that achieve

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simple but distinct tasks when subject to particular stimuli. Clever combinations of these simple behaviors results in the emergence of more intelligent behavior suitable for dealing with more complex situations. Fuzzy logic control and behavior control share common advantages for designing intelligent systems. Namely, they both require short development times and incorporate flexibility in their design. Individual fuzzy rules (and behaviors) can be formulated independently, and additional rules (and behaviors) can easily be added to the control system if necessary. Recent research [8,9] has recognized the practicality of integrating fuzzy reasoning with reactive behavior control of mobile robots for the purpose of task-directed navigation. A logical next step is toward autonomous mapping.

2. Mapping Issues

In order to facilitate later navigation and planning, a map generated by an autonomous mobile robot system should be in a form that is useful for local, as well as global, navigation. While previous work has shown [5] that fuzzy controlled robots are fairly robust at avoiding obstacles during local navigation, the behaviors they possess may be inadequate for deciding which way the robot should proceed around obstacles. Indeed, a given direction may lead to a dead-end, thus requiring significant backtracking. Such knowledge may be very useful for efficient exploration and subsequent planning. A useful robot map must be space efficient and easy to retrieve and maintain [10]. This suggests a preference for representations other than topographical maps which can be quite memory intensive. Processes that interpret or modify such maps also tend to be computationally intensive. For successful integration of fuzzy reasoning with low-level behavior control, stored information should be maintained at a high level of abstraction. That is, stored state should represent approximate descriptions of the actual world state. A suitable form of representation is the topological map which specifies distinct objects or places and connections among them.

Another mapping issue to be reckoned with, from an algorithmic standpoint, is sensor error and inaccuracy. Mobile systems with modest computational resources are typically equipped with inexpensive range sensors such as infrared and/or sonar. The problems encountered with these sensors are well known. The reliability of sensory data collected from infrared sensors is affected by the reflective properties of obstacles in the environment. As a result, the quality of range data operated on by a fuzzy controller is suspect. When using sonar ranging to reason about the state of the world we must be prepared to handle the inaccurate sensory information which is inherent in sonar-based systems. Ideally, when sonar pulses are emitted against a surface they are reflected from that surface to a receiver, thus allowing for range calculation based on the speed of sound and time of flight of the pulse. In practice, however, it is quite common for the sonar pulse to be reflected from the initial surface, to other surfaces and finally back to the receiver, yielding incorrect range calculations. Such specular reflections make obstacles appear to be closer to, or farther away from, the robot. Specular reflection is a predominant source of error, particularly outdoors where surfaces are generally rough. The specular reflection problem inherent in sonar range finders is similar to the problem humans face when inside of a house of mirrors. In such environments, the human vision system is quite susceptible to false positive readings despite its complexity and otherwise robust performance. As such, the potential for false positive readings in the world directly impacts the algorithms used to navigate throughout. Reactive fuzzy controlled mobile robots are particularly good at safely wandering throughout unknown territory. Behavior control robots exhibit comparable performance when faced with more complex navigation tasks. A combination of these attributes should be adequate for addressing most of the important issues involved in autonomous mapping.

3. Fuzzy Control

Fuzzy logic based controllers are expert control systems that smoothly interpolate between rules. Rules fire to continuous degrees and the multiple resultant actions are combined into an interpolated result. Processing of uncertain information and saving of energy using common-sense rules and natural language statements are the basis for fuzzy logic control.

A fuzzy controller typically takes the form of a set of IF-THEN rules whose antecedents and consequents are membership functions. Consequents from different rules are numerically combined (typically union via MAX) and are then collapsed to yield a single real number output. Fuzzy sets may be represented by a mathematical formulation often known as the membership function. This function gives a degree or grade of membership within the set. The membership function of a fuzzy set A, denoted by $\mu_{A(X)}$ maps the elements of the universe X into a numerical value within the range [0,1], i.e.

$$\mu_{A(X)}: X \text{ ------> } [0,1] .$$

Note that a membership function is a so-called *possibility* function and not a probability function. In control system applications membership values are actually measures of degree of causality in an input-output mapping. Fuzzy logic gave a new definition to the causality in dynamic systems. Within this framework, a membership value of zero corresponds to an element which is definitely not a member of the fuzzy set, while a value of one corresponds to the case where the element is definitely a member of the set [11]. Implementation of a fuzzy controller requires assigning membership functions for both inputs and outputs. For example, our collision avoidance controller [5] has a set of three inputs and two outputs. The inputs are frontal obstacle range, and left and right obstacle proximities; the outputs are the steering direction and vehicle speed. The fuzzy rule base would then consist of a set of IF-THEN rules that map fuzzy range variables into fuzzy heading and speed commands. Typical IF-THEN rules in our collision avoidance system are:

IF range is NEAR and left-prox is CLEAR and
  right-prox is NOTCLEAR
THEN heading is LEFT and speed is SLOW

IF range is FAR and left-prox is NOTCLEAR and
  right-prox is NOTCLEAR
THEN heading is SAME and speed is FAST

The uppercase terms are fuzzy sets defined on appropriate universes of discourse (see [5] for details). Using a set of rules such as these, a finite number of rules can be derived in the form of natural language statements to implement collision avoidance for navigation and mapping.

4. Behavior Control

The robot behaviors used in applying the behavior control paradigm employ transfer *functionals* (rather than the transfer functions of classical control theory) from sensor inputs to actuator outputs [7]. Transfer functionals are fairly simple computational mechanisms whose output can contain stored internal state. In principal, behavior control can be applied in situations where classical control theory is not feasible, usually due to tremendous modelling difficulties. The collection of mobile robot behaviors useful for mapping is comprised of primitive behaviors and composite behaviors. These behaviors can easily be designed using the theory of fuzzy sets as demonstrated by Pin and Watanabe [8].

Primitive behaviors are, generally, open-loop transfer functionals such as simple movement, servo-to-heading, turn-until-clear, wander/explore, and obstacle-avoidance. These can function as stand-alone behaviors or as building blocks for the more complex composite behaviors. Composite behaviors, on the other hand, are closed-loop functionals that continuously sense and react to local changes in the robot's world. Examples of composite behaviors are follow-wall, follow-boundary, and circumnavigate-obstacle.

Additional task-directed behaviors can be employed in the mapping system. These are simply constructed from the primitive and/or composite behaviors described above. For example, a task-directed behavior called circumnavigate-and-map-obstacle, is merely an aggregation of the obstacle-avoidance, turn-until-clear, and follow-boundary behaviors (the function of this behavior should be obvious from its name). The incorporation of new behaviors into the system is trivial; and as system development continues, this is an inevitability.

5. Mapping Strategy

The task of mapping unknown environments calls for the capability to look around the environment, determine the locations and occupancies of all obstacles and place them in a map (typically two dimensional). This is usually done for the purpose of subsequently using the map to safely and successfully perform useful tasks within. We assume that no map is available a priori, and consequently, there is no immediate "goal" directive. Thus, the initial navigation activity of a reactive mapping robot is governed by a general explore and wander scheme along with a mapping activity [12]. A general exploration and mapping strategy for bounded regions could consist of the following steps:

1. Specify a short travel distance after which sensor readings will be periodically taken, delta-d
2. Move along the robot's current heading until either delta-d OR some time, delta-t expires
3. Check whether sensors indicate an obstacle in detectable range
4. If an obstacle is encountered store reading and check sensors again
   - if consistent (something still in detectable range, or reading decreasing), approach the obstacle to within mapping range
   - if the obstacle has been mapped before, avoid it otherwise, map it (Go to step 6)
5. Turn the robot to a random heading between +/- 90 degrees from its current heading (Go to step 2)
6. Map the obstacle and insert a representation of it into the map
7. Turn the robot to a new explore heading that is oriented away from the obstacle just mapped and toward free space (Go to step 2).

This strategy would begin at a designated "home" location and terminate when the region is sufficiently mapped. Eventually, the information collected can be represented in a two dimensional topological map that reveals an approximate distribution of obstacles in the region of interest. Furthermore, the uncertainty of this distribution can be represented in a "fuzzy Cartesian system" where coordinates are approximate locations of objects mapped by the robot. Figure 1 illustrates the idea of a 2-D fuzzy Cartesian space.

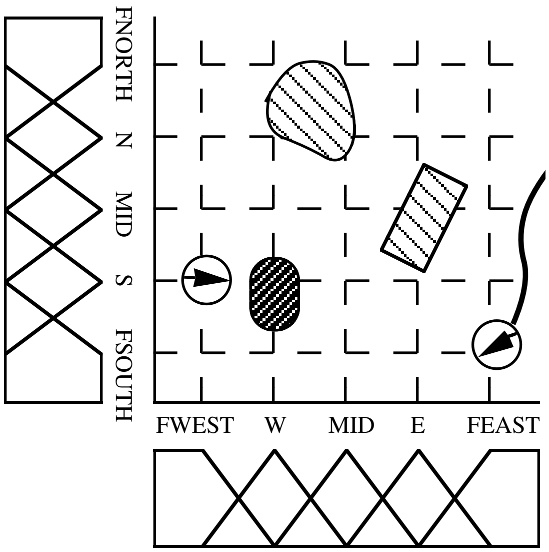

Figure 1. Fuzzy Cartesian coordinate system

The ordinate and abscissa are partitioned using fuzzy sets with labels designating varying degrees of north, south, east, and west (the F indicates Far). The robot is represented by the circle with the arrow indicating its direction. In this representation the darkened object, for example, is located at a fuzzy coordinate of south-west. Any other location can be similarly represented using any desired fuzzy set resolution on the ordinate and abscissa.

6. Summary

We have discussed a possible strategy for autonomous mobile robot mapping using a combination of the attributes of fuzzy and behavior control. The motivation stems from the desire to relax the requirement for explicit world maps and reduce the associated computational burden. The development of the necessary algorithms would enable real-time map-based navigation for mobile robots in previously unknown environments. Progress is being made towards development of a suitable simulation environment and plans for actual implementation of the strategy on a behavior-controlled mobile robot are underway.

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