MOBILE ROBOT AUTONOMY VIA HIERARCHICAL FUZZY BEHAVIOR CONTROL

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ABSTRACT

Realization of autonomous behavior in mobile robots, using fuzzy logic control, requires formulation of rules which are collectively responsible for necessary levels of intelligence. This collection of rules can be conveniently decomposed and efficiently implemented as a hierarchy of fuzzy-behaviors. This paper describes how this can be done using a behavior-based architecture. The approach is motivated by ethological models which suggest hierarchical organizations of behavior. A behavior hierarchy and mechanisms of control decision-making are described. Simulation predicts performance and reveals characteristics of behavior interaction.

KEYWORDS: mobile robot, fuzzy-behavior, behavior hierarchy

INTRODUCTION

Robust behavior in autonomous robots requires that uncertainty be accommodated by the robot control system. Fuzzy logic is particularly well suited for implementing such controllers due to its capabilities of inference and approximate reasoning under uncertainty. Many fuzzy controllers proposed in the literature utilize a monolithic rule-base structure. That is, the precepts that govern desired system behavior are encapsulated as a single collection of *if-then* rules. In most instances, the rule-base is designed to carry out a single control policy or goal. In order to achieve autonomy, mobile robots 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. This requires formulation of a large and complex set of fuzzy rules. In this situation a potential limitation to the utility of the monolithic fuzzy controller becomes apparent. Since the size of complete monolithic rule-bases increases exponentially with the number of input variables [1], multi-input systems can potentially suffer degradations in real-time response. This is a critical issue for mobile robots operating in dynamic surroundings.

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Hierarchical rule structures can be employed to overcome this limitation by reducing the rate of increase to linear [1, 2].

This paper describes a hierarchical behavior-based control architecture. It is structured as a hierarchy of fuzzy rule-bases 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. A fuzzy coordination scheme is also described that employs weighted decision-making based on contextual behavior activation. Performance is demonstrated by simulation highlighting interesting aspects of the decision-making process which arise from behavior interaction.

HIERARCHICAL BEHAVIOR CONTROL

The behavior control paradigm has grown out of an amalgamation of ideas from ethology, control theory and artificial intelligence [3, 4]. 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. The paradigm was initially proposed by Brooks [4] and realized as the 'subsumption architecture' wherein a behavior system is implemented as distributed finite state automata. Until recently [5, 6, 7], most behavior controllers have been based on crisp (non-fuzzy) data processing and binary logic-based reasoning. 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. Thus, each fuzzy-behavior is similar to the conventional fuzzy controller in that it performs an inference mapping from some input space to some output space. 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 $\tilde{B}_i$".

Behavior Hierarchy

The proposed architecture is a conceptual model of an intelligent behavior system and its behavioral relationships. Overall robot behavior is decomposed into a bottom-up hierarchy of increased behavioral complexity in which activity at a given level is dependent upon behaviors at the level(s) below. 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 robot's sensor suite to (typically, but not necessarily) common actuators. Each

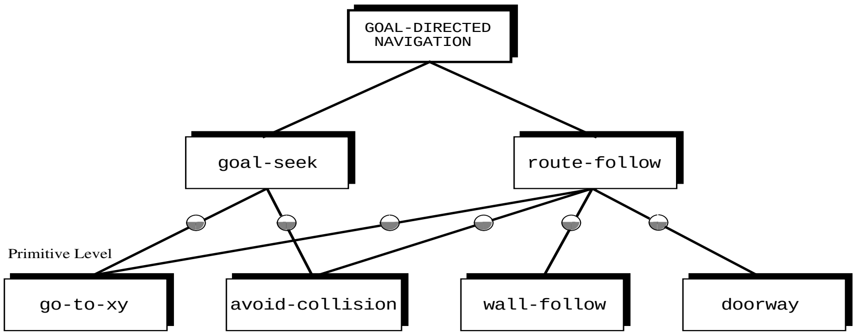

Figure 1. Hierarchical decomposition of mobile robot behavior.

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 operations.

A behavior hierarchy for indoor navigation might be organized as in Figure 1. It implies that goal-directed navigation can be decomposed as a behavioral function of `goal-seek` and `route-follow`. These behaviors can be further decomposed into the primitive behaviors shown, with dependencies indicated by the adjoining lines. `Avoid-collision` and `wall-follow` are self-explanatory. The `doorway` behavior guides a robot through narrow passageways in walls; `go-to-xy` directs motion along a straight line trajectory to a particular location. The circles represent weights and activation thresholds of associated primitive behaviors. As described below, 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 mobile robot system 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.

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 [8]. 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 α_j for the situation prevailing during the current control cycle. This feature allows certain robot 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 robot's behavior during a given control cycle. 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. The reduction in rule evaluations is not as dramatic or static as in the strict rule hierarchies proposed in [1, 2] since we are dealing with a *behavior* hierarchy that achieves interacting goals. As such, the number of rules consulted during each control cycle varies dynamically as governed by the DOAs and thresholds of the behaviors involved.

Coordination and conflict resolution are achieved within the framework of fuzzy logic theory — via operations on fuzzy sets [9]. Fuzzy rules of each applicable primitive behavior are processed yielding respective output fuzzy sets. These fuzzy sets are equivalent to the result produced by rule-base evaluation in conventional fuzzy controllers *before* applying the defuzzification operator. Following consultation of applicable behaviors, 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 using an appropriate t-conorm operator (e.g. *max*), 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.

NAVIGATION EXAMPLE

In order to demonstrate the operational aspects of the controller in the simplest manner possible we consider only the composite behavior — `goal-seek`. As illustrated in Figure 1, its effect arises from synergistic interaction between primitive behaviors, `go-to-xy` and `avoid-collision`. 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 simulated mobile robot is modeled after LOBOt, a custom-built base with a 2-wheel differential drive and two stabilizing casters. It is octagonal in shape, 75 cm tall and 60 cm in width. The sensor suite includes optical encoders on each driven wheel and 16 ultrasonic transducers arranged primarily on the front, sides, and forward-facing obliques. The simulated "world" is a hypothetical indoor layout not unlike a warehouse or office

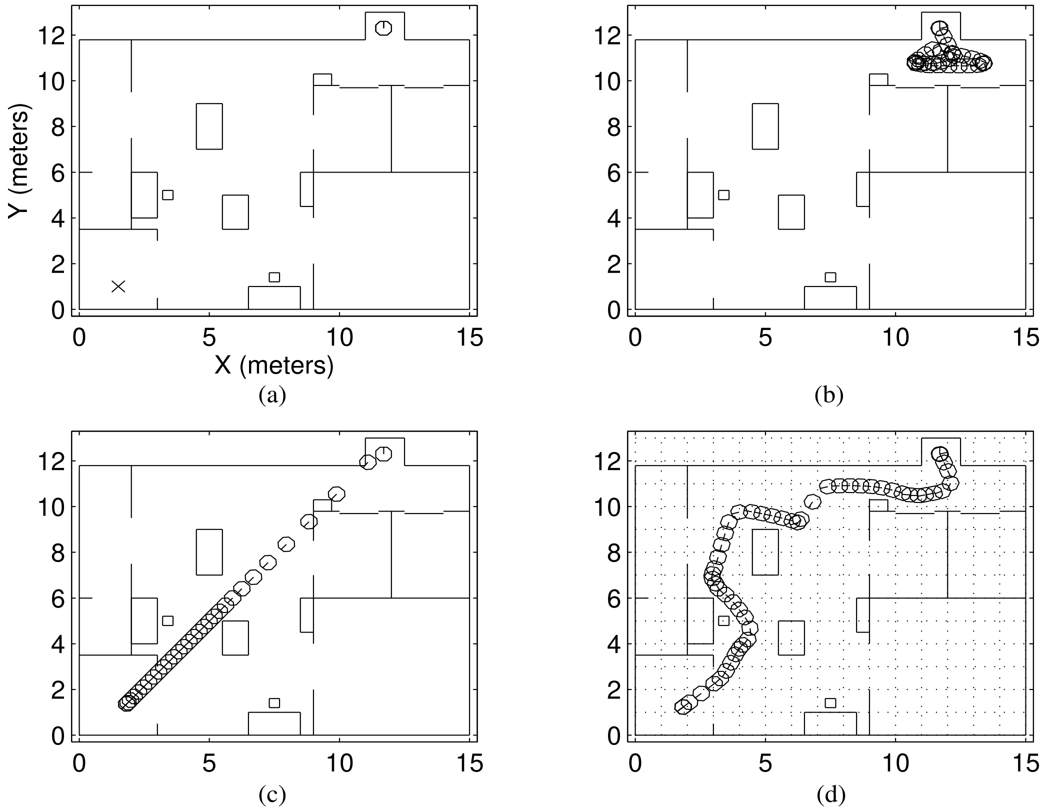

Figure 2. Simulation of goal-seeking behavior.

building. The initial state of the simulation is shown in Figure 2a with LOBOt located at its docking station with pose $\mathbf{p} = (11.7\ 12.3\ \frac{\pi}{2})^T$. Its task is to navigate to the goal located at $(1.5, 1)$, marked by the X. The `avoid-collision` and `go-to-xy` behaviors are each shown acting alone in Figure 2 b and c, respectively. Recall that these behaviors are only capable of exhibiting their particular primitive roles. Thus, `avoid-collision` merely displays cyclic collision-free motion in the immediate vicinity of the robot's initial location, while `go-to-xy` displays a taxic reaction that propels the robot toward the goal irregardless of obstacles in its path. Successful completion of the task, resulting from adaptive coordination of the primitive behaviors, is shown in Figure 2d.

In Figure 3, 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 brief bouts of competition (overlapping oscillations) and cooperation with varying levels of dominance. Initially, `avoid-collision` has the dominant influence over the robot due to the close proximity of walls at the docking station. It virtually maintains dominance throughout the task due to the relatively uniform clutter in the environment. The first bout of competition corresponds to the robot's approach toward the obstacle located at $(5, 8)$; a second bout occurs as it enters the goal room. Elsewhere, applicabilities vary continuously reflecting levels of activation recommended by the behavior control system.

CONCLUSION

The hierarchy of fuzzy-behaviors provides an efficient approach to controlling mobile robots. Its practical utility lies in the decomposition of overall behavior into sub-behaviors that are

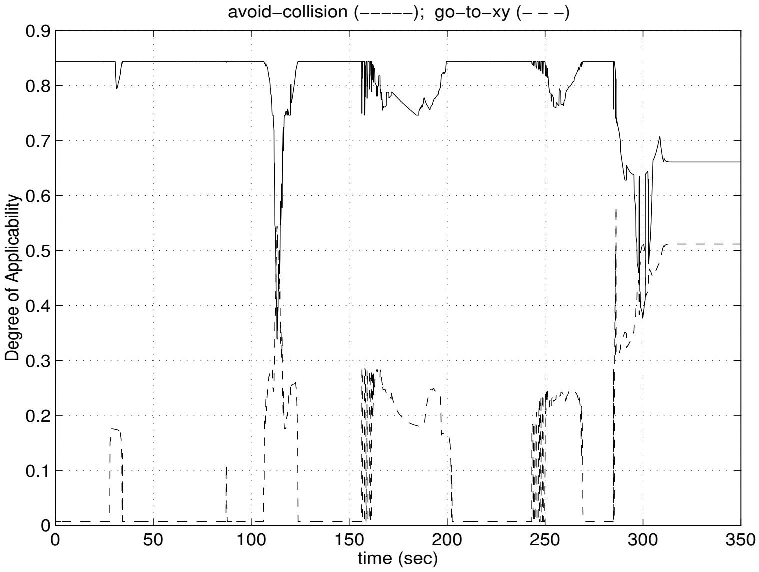

Figure 3. Behavior interaction during goal-seeking.

activated only when applicable. When conditions for activation of a single behavior (or several) are satisfied, there is no need to process rules from behaviors that do not apply. This would result in unnecessary consumption of computational resources and possible introduction of "noise" into the decision-making process. 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 robots. To date, simulations have been used to predict the performance of a real robot on which real-time experiments are currently being prepared.

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