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Behavior Based Control of A Mobile Robot in Unknown Environments Using Fuzzy Logic *

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Abstract: This paper presents a new method for behavior based control of a mobile robot in uncertain environments using fuzzy logic. Behavior based control suffers from two difficulties: ① The quantitative formulation of behavior; ② The efficient coordination of conflicts and competition among multiple behavior. The main idea of the present study is to incorporate fuzzy logic control with behavior based control such that: behavior is formulated by fuzzy sets and a rule base; conflicts and competition among different behavior are coordinated by fuzzy reasoning.

Simulation results show that the proposed method can be efficiently applied to robot navigation in complex and unknown environments by fusing multiple behavior, such as avoiding obstacles, following edges, and moving towards a target, and so forth. In addition, this method is suitable for robot navigation by multisensor fusion and integration.

Key words: behavior based control; fuzzy logic control; robot navigation; uncertainty; sensor based motion planning

1 Introduction

A key issue in applying an autonomous robot into new fields is its navigation in unknown and complex environments. If a mobile robot moves among unknown obstacles to reach a specified target without collisions, sensors must be used to acquire information about the real world. Using such information, however, it is very difficult to build a precise and entire world model in real-time for preplanning a collision-free path. On the basis of stimulus-response behavior in bio-systems, behavior-based control[1,2] has been proposed for robot navigation in dynamic environments since this control method does not need building an exact world model and complex reasoning process. Behavior based control, however, suffers from two difficulties: ① The quantitative formulation of behavior; ② The efficient coordination of conflicts and competition among multiple behavior.

The usual approach for formulating behavior is to use artificial potential fields [4,5]. A drawback to the approach is that during preprogramming much effort must be made to test and to adjust some thresholds regarding potential field for avoiding obstacles, wandering, and moving towards a target, and so forth. Furthermore, these thresholds heavily

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depend on environment, so this approach is very fragile for robot navigation in dynamic environment. In [1], the coordination of multiple behavior is done by inhibiting those behavior with lower urgency levels. However, this strategy is highly contentious when a mobile robot executes tasks in complex environment. The example in Fig. 1 shows that, according to range information, the robot must efficiently fuse multiple behavior, such as avoiding obstacles, following edges, and moving towards a target etc., so that it can reach a target inside a U-shaped object.

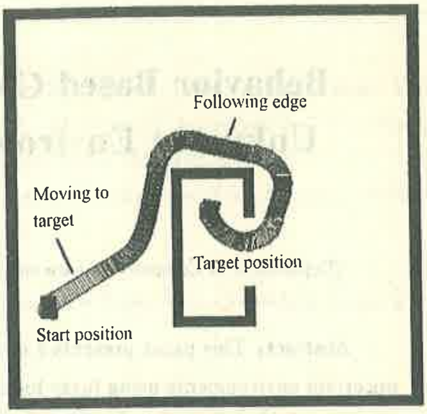


Fig. 1 Robot motion to reach a target inside a U-shaped object

This paper presents a new method for behavior control based on fuzzy logic[6,7]. Unlike behavior control based on artificial potential fields, this method is to fuse multiple behavior by fuzzy logic algorithm rather than simply to inhibit those behavior according to their priorities. This method also differs from the fuzzy control approaches for obstacle avoidance in [8~10] since perception and decision units in this method are integrated in one module by the use of the idea of behavior control, and they are directly oriented to a dynamic environment to improve real-time response and reliability. To demonstrate the effectiveness and the robustness of the proposed method, we report simulation results on robot navigation in unknown environment, such as moving obstacle avoidance in real-time, decelerating on curved and narrow roads, escaping from a U-shaped object and moving towards a target, and so on.

2 Fuzzy Logic Control and Behavior Based Control

Fuzzy logic control is based on the theory of fuzzy sets, as introduced by Zadeh[11]. A fuzzy set in a universe of discourse X is defined by its membership function $\mu_A(x)$. For each $x \in X$, there exists a value $\mu_A(x) \in [0,1]$ representing the degree of membership of x in X. In fuzzy logic control membership functions, assigned with linguistic variables, are used to fuzzify physical quantities. Fuzzified imputs are inferred to a fuzzy rule base. This rule base is used to characterize the relationship between fuzzy inputs and fuzzy outputs. For example, a simple fuzzy control rule relating input v to output u might be expressed in the condition-action form as follows:

$$\text{If } v \text{ is } W \text{ Then } u \text{ is } Y.$$

Where W and Y are fuzzy values defined on the universes of v and u, respectively. The response of each fuzzy rule is weighted according to the degree of membership of its input conditions. The inference engine provides a set of control actions according to fuzzified inputs. Since the control actions are in fuzzy sense, hence a defuzzification method is required to transform fuzzy control actions into a crisp output value of the fuzzy logic controller. A widely used defuzzification method is the centroid method:

$$\bar{u} = \Big(\sum_{i=1}^{n}\mu_Y(c_i) * c_i\Big)\Big/\Big(\sum_{i=1}^{n}\mu_Y(c_i)\Big). \quad (1)$$

Where $\bar{u}$ is a crisp output value of the controller, n is the number of control rules associated with the fuzzified inputs, and c_i is the centroid of membership function associated with each linguistic value in the output space.

Behavior-based control is based on the stimulus-response behavior in bio-systems. Its idea is used to decompose robot complex tasks into behavior with simple features. However, the difficulties in behavior-based control arise mainly from the quantitative formulation of behavior as well as from the need for the efficient coordination and integration of conflicts and competition among different behavior.

Since both behavior-based control and fuzzy logic control can be specified to the expert system in the form of production rules, behavior-based control can be quantitatively formulated by using fuzzy sets and fuzzy rules. For instance, robot wandering behavior can be described by the following If "conditions" Then "actions" statements:

If obstacles are located to the left of a robot Then the robot turns to the right

If obstacles are located to the right of a robot Then the robot turns to the left

Such statements can be quantitatively formulated by defining linguistic variables and their membership functions with ease. In addition, the problem of coordinating conflicts and competition among different behavior can be dealt with by fuzzy reasoning.

3 Fuzzy Logic Control Scheme for A Mobile Robot

In order to acquire information about dynamic environment, 15 ultrasonic sensors are mounted on the THMR-Ⅱ mobile robot with 1.0m length and 0.8m width. These ultrasonic sensors are divided into three groups to detect obstacles to the left, front, right locations, as shown in Fig. 2, respectively. The THMR-Ⅱ mobile robot is equipped with two driving wheels and one driven wheel. The velocities of the driving wheels are controlled by a motor drive unit. The input signals to fuzzy logic navigation algorithm are distances between the robot and obstacles to the left, front, and right locations as well as the heading angle between the robot and a specified target, denoted by left-obs, front-obs, right-obs and head-ang, respectively, as shown in Fig. 3(a). When the target is located to the left side of the mobile robot, a heading angle head-ang is defined as negative; when the target is located to the right side of the mobile robot, a heading angle head-ang is defined as positive, as shown in Fig. 3(b). According to acquired range information, behavior is weighted by

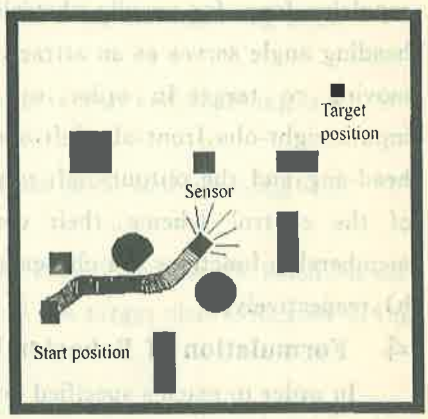


Fig. 2 Ultrasonic sensor-based robot motion

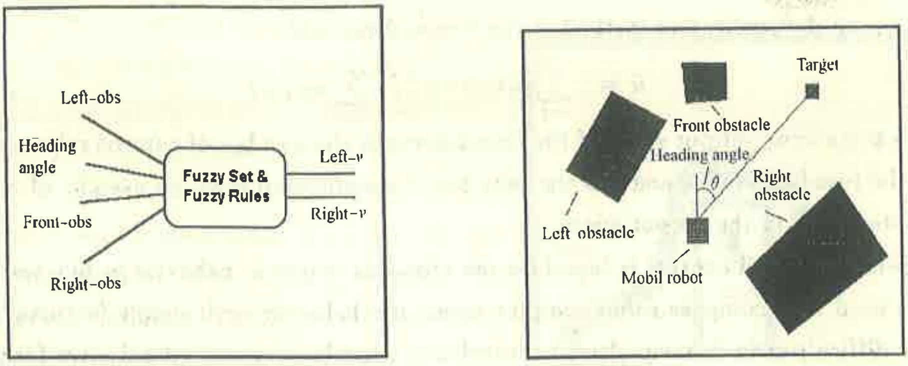
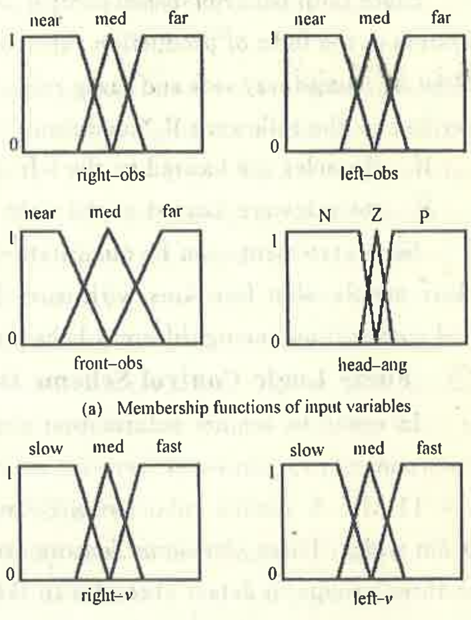


Fig. 3 Fuzzy logic control scheme for behavior based control of a mobile robot

the fuzzy logic algorithm to control the velocities of the two driving wheels of the robot, denoted by left-v and right-v, respectively. The linguistic variables far, med (medium) and near are chosen to fuzzify left-obs, front-obs and ritht-obs. The linguistic variables P(positive), Z(zero) and N(negative) are used to fuzzifiy head-ang; the linguistic variables fast, med, and slow are used to fuzzify the velocities of the driving wheels left-v and right-v. In analogy to artificial potential field, distances between the robot and obstacles serve as a repulsive force for avoidig obstacle, while the heading angle serves as an attractive force for moving to target. In order to fuzzify the inputs, right-obs, front-obs, left-obs, and head-ang; and the outputs, left-v and ritht-v, of the control scheme, their corresponding membership functions are chosen in Fig. 4(a, b), respectively.



(a) Membership functions of input variables

(b) Membership functions of output variables

Fig. 4 Membership functions of inputs and outputs

4 Formulation of Behavior Using Fuzzy Logic

In order to reach a specified target in a complex environment, the mobile robot must at least have the following behavior: ① obstacle avoidance; ② following edges; ③ target steer; ④ decelerating on curved and narrow roads. Because a real world is very complex, using ultrasonic sensors it is very difficult to acquire precise information about dynamic environment. In this case, a set of fuzzy logic rules is used to describe the perception-action behavior mentioned above. Now, we list parts of fuzzy rules from the rule base to explain, in principle, how the perception-action behavior is realized (in fact, much more fuzzy logic rules have been used in our navigation algorithms).

4.1 Obstacle Avoidance and Decelerating on Curved and Narrow Roads

When the acquired information from the ultrasonic sensors shows that there exist obstacles nearby robot or the robot moves on curved and narrow roads, it must reduce its speed to avoid obstacles. In this case, its main behavior is decelerating for obstacle avoidance. To realize this behavior, we use such fuzzy logic rules as follows:

If left-obs is near and front-obs is near and right-obs is near and head-ang is any
Then left-v is fast and right-v is slow
If left-obs is med and front-obs is near and right-obs is near and head-ang is any
Then left-v is slow and right-v is fast
If left-obs is near and front-obs is near and right-obs is med and head-ang is any
Then left-v is fast and right-v is slow
If left-obs is near and front-obs is med and right-obs is near and head-ang is any
Then left-v is med and right-v is med

Such fuzzy rules represent that the robot only pays attention for obstacle avoidance and moves slowly when it is very close to obstacles or on curved and narrow roads.

4.2 Following Edges

When the robot is moving to a specified target inside a room (Fig. 1) or escaping from a U-shaped obstacle, it must reflect following edge behavior. In order to describe this behavior, we use the following fuzzy rules:

If left-obs is far and front-obs is far and right-obs is near and head-ang is P
Then left-v is med and right-v is med
If left-obs is near and front-obs is far and right-obs is far and head-ang is N
Then left-v is med and right-v is med
If left-obs is far and front-obs is med and right-obs is near and head-ang is P
then left-v is med and right-v is med
If left-obs is near and front-obs is med and right-obs is far and head-ang is N
Then left-v is med and right-v is med

These fuzzy rules show that the robot shall follow an edge of an obstacle when the obstacle is very close to the left (or right) of the robot and the target also is located to the left (or right).

4.3 Target Steer

When the acquired information from the ultrasonic sensors shows that there are no obstacles around robot, its main behavior is target steer. Here, we use the following fuzzy rules to realize this behavior:

If left-obs is far and front-obs is far and right-obs is far and head-ang is Z
Then left-v is fast and right-v is fast
If left-obs is far and front-obs is far and right-obs is far and head-ang is N
Then left-v is slow and right-v is fast

If left-obs is far and front-obs is far and right-obs is far and head-ang is P

Then left-v is fast and right-v is slow

These fuzzy logic rules show that the robot mainly adjusts its motion direction and quickly moves to the target if there are no obstacles around the robot.

4.4 Coordination of Multiple Behavior

In behavior control based on artificial potential fields, the velocities of the driving wheels left-v and right-v are controlled by a behavior that is determined by inhibiting behavior with lower levels according their priorities. In doing this, much effort must be made to test and to adjust some thresholds during preprogramming. Besides, these thresholds usually depend on environment. In our 'perception-action' behavior control, behavior is formulated by fuzzy rules and the velocities of the driving wheels left-v and right-v are determined by weighting the behavior. This is done by the min-max inference algorithm and the centroid defuzzification method. This strategy for the coordination of multiple behavior is not to inhibit those 'perception-action' behavior with lower levels, so this is more reasonable for robot navigation.

5 Simulations

To demonstrate the effectiveness and the robustness of the proposed method, here we report several simulation results on robot navigation in dynamic environment using ultrasonic sensors, such as avoiding obstacle in real-time, decelerating on curved and narrow roads, escaping from a U-shaped object and moving to target, and so on.

5.1 Moving Towards a Target inside a U-Shaped Object

Fig. 1 illustrates robot motion to a target inside a U-shaped object. At start stage, the robot moves to the target at a high speed since the "moving to target" behavior is strong due to the large free space around the robot. When the robot approaches to the U-shaped object, it is decelerating by automatically reducing the weight of the "moving to target" behavior and increasing the weight of both "avoiding obstacle" and "following edge" behavior. When the robot finds out the entry of the U-shaped object, it slowly reaches the target by integrating both "avoiding obstacle" and "moving to target" behavior.

5.2 Escaping from a U-Shaped Object

Fig. 5 shows a robot start position is located to the entry side of the U-shaped object and a target position is located to the back side of the U-shaped object. In this case, using artificial potential field the robot is usually trapped inside the U-shaped obstacle due to local minimum. Using our navigation algorithm, the robot moves to the target at a high speed at start stage since there is a large free space around the robot. When it is trapped inside the U-shaped object, the robot is moving along the edge of the U-shape object by increasing the weight of the "following edge" behavior as so to escape the U-shaped object. When the robot goes around the U-shaped object, it drives to the target at a high speed again.

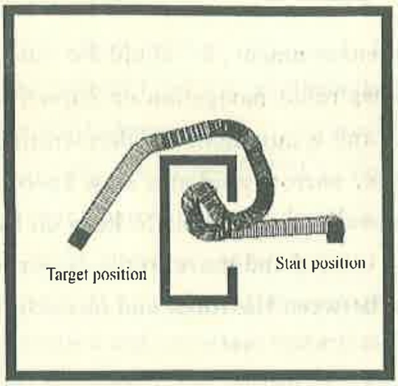


Fig. 5 Robot motion to a target with excaping from the *U*-shaped object

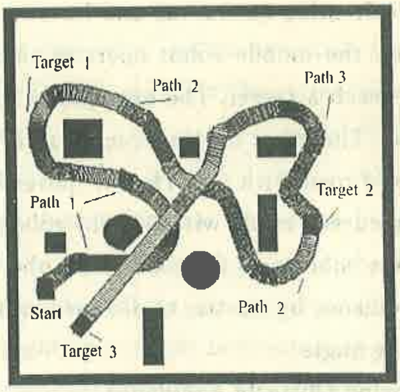


Fig. 6 Robot motion to reach multiple targets in a cluttered environment

5.3 Moving in a Cluttered Environment

Fig. 6 shows the robot motion in a cluttered environment. We choose at random several targets that are located among different obstacle distribution. Path 1 in Fig. 6 represents robot motion from the start position to target 1 located in a narrow road;Path 2 in Fig. 6 represents robot motion from target 1 to target 2 that is behind more obstacles;and path 3 represents robot motion from target 2 to target 3 that is placed in the region where the start position is located. It can be observed that,only using ultrasonic sensors to acquire range information,the robot can successfully reach all targets by efficiently weighting multiple 'perception-action' behavior using fuzzy logic.

5.4 Following Wall Edges

In some applications,a mobile robot should be able to move from a room to another. Fig. 7 shows that a start position and a target position are located in different rooms. Using artificial potential field,it is difficult for the robot to reach the target in absence of complete information about the environment. Using our navigation algorithm, however, the robot can automatically act "following edge" behavior (in our algorithm the right-oriented principle is implemented) as so to reach the target when it "hits" the wall.

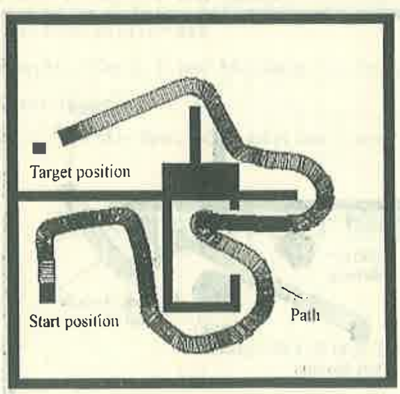


Fig. 7 Robot motion to reach a target by following edge behavior

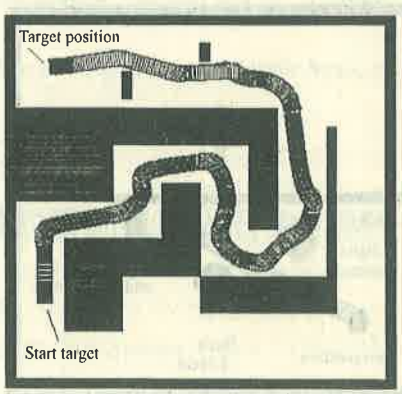


Fig. 8 Robot motion with lower speed at curved and narrow roads

5.5 Decelerating on Curved and Narrow Roads

When the mobile robot operates in outdoor environment, it should be able to tack roads to reach a target. The example in Fig. 8 shows robot navigation on curved and narrow roads. The robot begins from its start position and is automatically decelerating on the first curved road with 90°. Then it moves into a very narrow road at a slow speed. On the following curved roads with 90°, the robot automatically makes turns to keep on the road. Finally, the robot gets the road where the target is located and move to the target with obstacle avoidance by the use of distance information between the robot and obstacles as well its heading angle.

5.6 Moving Obstacle Avoidance

Fig. 9(a~d) shows the simulation of robot motion in an uncertain environment with avoiding a moving obstacle. In the example, we set a moving obstacle nearby the target whose speed is lower than that of the mobile robot. Its motion direction is along the wall and just blocks the robot motion to the target in Fig. 9(a). In this case, the robot only pays attention for avoiding this obstacle by making right turn, as shown in Fig. 9(a, b). After the robot goes round the moving obstacle, it moves directly to the target in Fig. 9(c, d).

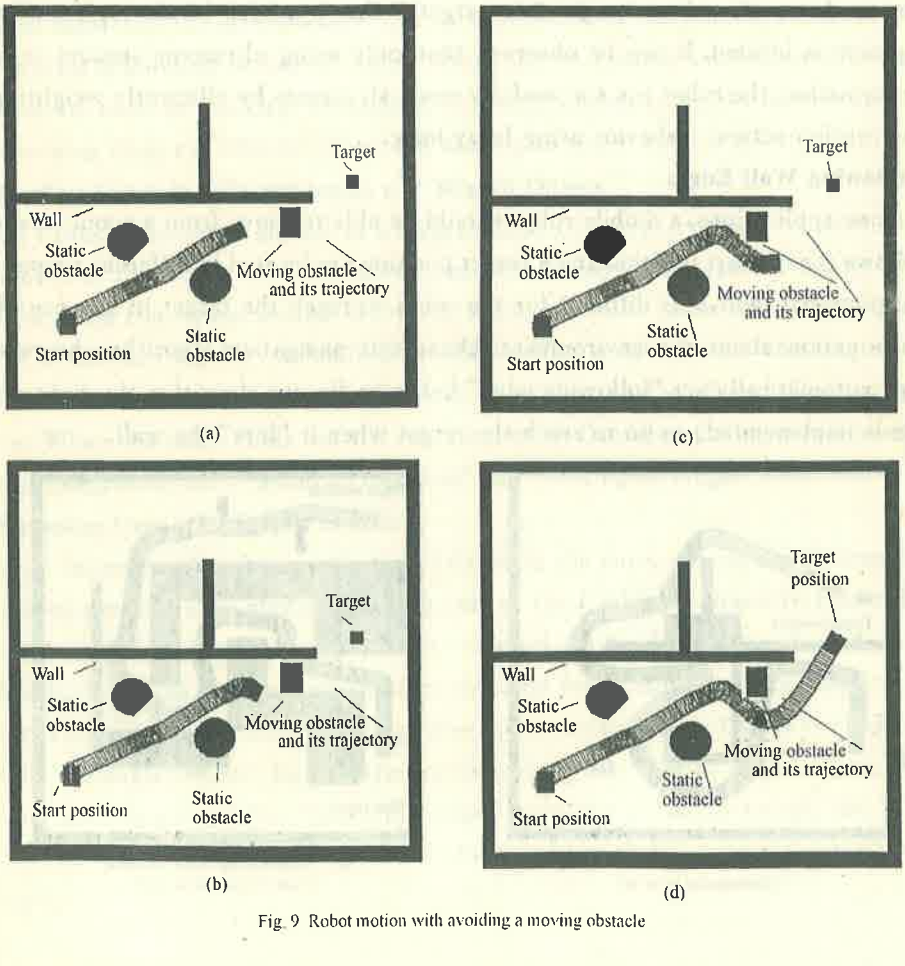


Fig. 9 Robot motion with avoiding a moving obstacle

6 Conclusions

In this paper, we use fuzzy logic to formulate behavior control for robot navigation. Since this method is to fuse multiple behavior by fuzzy logic algorithm rather than simply to inhibit the behavior with lower level according to the priorities, it is more efficient than traditional behavior control. The navigation algorithm has better reliability and real-time response since perception and decision units are integrated in one module and are directly oriented to a dynamic environment. The simulation results show that the proposed method, only using information acquired by ultrasonic sensors, can perform robot navigation in complex and uncertain environment by weighting multiple behavior such as avoiding obstacles, decelerating at curved and narrow roads, escaping from a U-shaped object, and moving to target, and so on.

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在未知环境中基于模糊逻辑的移动机器人行为控制

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摘要：本文介绍了一种在未知环境中基于模糊逻辑的移动机器人行为控制方法. 传统的行为控制方法

存在两个弱点：① 行为不易描述；② 多个行为之间的冲突和竞争难以协调. 这篇文章的主要思想是将模糊逻辑控制与行为控制相结合致使这两个问题得到有效的解决. 仿真实验结果表明：所提的方法通过多个行为如避障边沿行走和目标导向的融合，能够有效地对机器人在复杂和未知环境中导航. 另外，该方法还适用于多传感器的融合与集成.

关键词：行为控制；模糊逻辑；机器人导航；非确定性；基于传感信息的规划

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