Proceedings of the 1994 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI'94) • Las Vegas, NV • Oct. 2-5, 1994

Fuzzy Logic Based Robot Navigation In Uncertain Environments By Multisensor Integration

Wei Li
National Laboratory of Intelligent Technology and Systems,
Department of Computer Science
Tsinghua University, Beijing (100084), China

Abstract—This paper presents a strategy for fuzzy logic based robot navigation in uncertain environments by multisensor integration. The main idea of the study is to coordinate conflicts and competitions among multiple reactive behaviors efficiently by fuzzy sets and a rule base. To achieve this objective, an array of ultrasonic sensors and a vision system are mounted on a mobile robot. The ultrasonic sensors provide distance information between the robot and obstacles for behavior control of the mobile robot, while the vision system identifies some subgoals for determining a good motion direction to avoid robot trap in local region. The simulation results show that the proposed strategy, by integrating ultrasonic sensors and the vision system, can be efficiently applied to robot navigation in complex and uncertain environments by using different behaviors, such as avoiding obstacles, decelerating at curved and narrow roads, escaping from a U-shaped object, and moving to target and so on.

I. Intrduction

If a mobile robot moves in unknown environments to reach a specified target without collisions with obstacles, sensors must be used to acquire information about the real world. Using such information, it is very difficult to build a precise world model in real-time for preplanning a collision-free path. On the basis of situationally reactive behaviors, behavior based control [1][2][3] has been proposed for robot navigation. Since this method does not need building an entire world model and complex reasoning process, it is suitable for robot control in dynamic environments. A key issue in behavior based control is how to coordinate conflicts and competitions among multiple reactive behaviors efficiently. The example in Fig.1 shows that the robot must efficiently weight multiple reactive behaviors, such as avoiding obstacle, following edge, and moving to target and so on., according to range information, when it reaches a target inside a U-shaped object. The usual approach for implementing behavior control is artificial potential fields [4][5][6]. A drawback to this approach is that during preprogramming much effort must be made to test and to adjust some thresholds regarding potential fields for avoiding obstacle, wandering, and moving to target and so on. In particular, these thresholds frequently depend on environments.

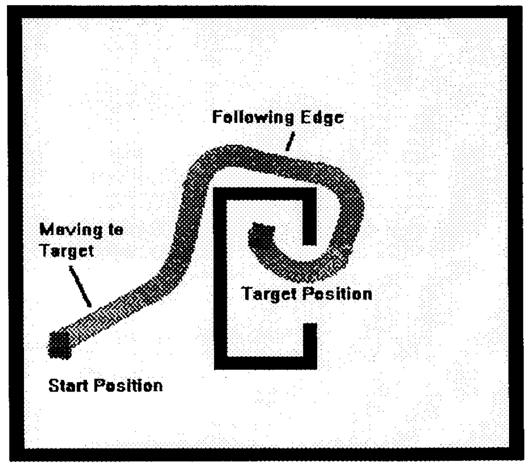


Fig.1: Robot motion to reach a target

In [7][8], we present an approach for fuzzy logic based behavior control of a mobile robot. Unlike behavior control based on artificial potential fields, this method is to compute weights of multiple reactive behaviors in dynamic environments by a fuzzy logic algorithm rather than simply to inhibit some reactive behaviors with lower levels. In this paper, we further present a strategy for fuzzy logic based behavior control of a mobile robot by multisensor integration. To achieve this objective, an array of ultrasonic sensors and a vision system are mounted on a mobile robot. The ultrasonic sensors provide distance information between the robot and obstacles for robot navigation by reactive behaviors, such as avoiding obstacles and following edges, while the vision system identifies some subgoals for determining a good motion direction to avoid robot trap in local region. This method differs from the fuzzy control approaches for obstacle avoidance in [9][10][11]. Since perception and decision units in this method are integrated in one module by the use of the idea of reactive behaviors and are directly oriented to a dynamic environment, this strategy has the better real-time response and reliability. To demonstrate the effectiveness and the robustness of the proposed strategy, we report a lot of simulation results on robot navigation in uncertain environments, such as avoiding obstacle in real-time, decelerating at curved and narrow roads, escaping from a U-shaped object and moving to target and so on.

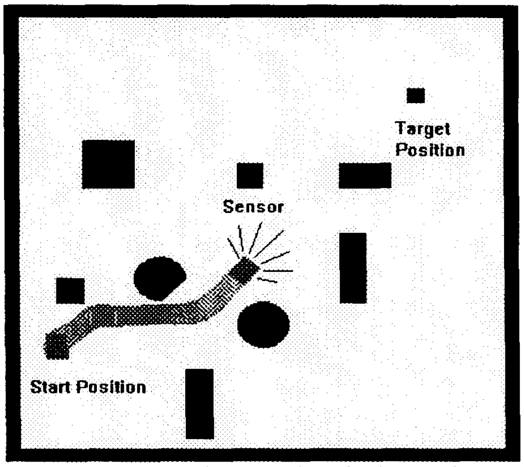


Fig.2: Ultrasonic sensor-based robot motion inside a U-shaped object

II. Ultrasonic Sensors

In order to acquire information about dynamic environments, 15 ultrasonic sensors are mounted on the THMR-II mobile robot [12], as shown in Fig.2. The sonar reflection from a sensor i represents the distance d_i, measured by the sensor i, between the robot and obstacles in the real world. These ultrasonic sensors are divided into three groups to detect obstacles to the right (sensor i = 1, ..., 6), front (sensor i = 7, ..., 9), and left locations (sensor i = 10, ..., 15). Using such information, obviously, it is difficult to build a precise and entire world model in real-time for preplanning a collision-free path. Here, we use the sonar data d_i (i = 1, ..., 15) to build a simple model for representation of the distances between the robot and obstacles in the real world as follows:

$$right\_obs = Min\{d_i\} \quad i = 1,..., 6 \tag{1}$$

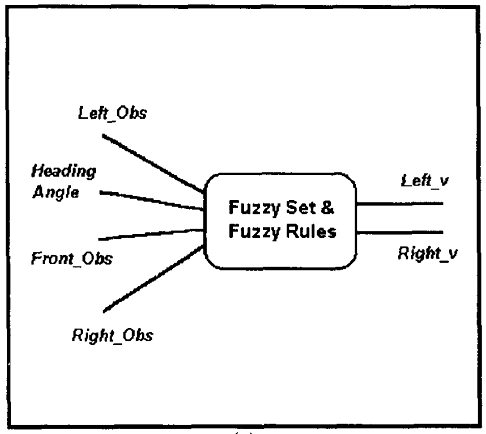
$$front\_obs = Min\{d_i\} \quad i = 7,..., 9 \tag{2}$$

$$left\_obs = Min\{d_i\} \quad i = 10,..., 15 \tag{3}$$

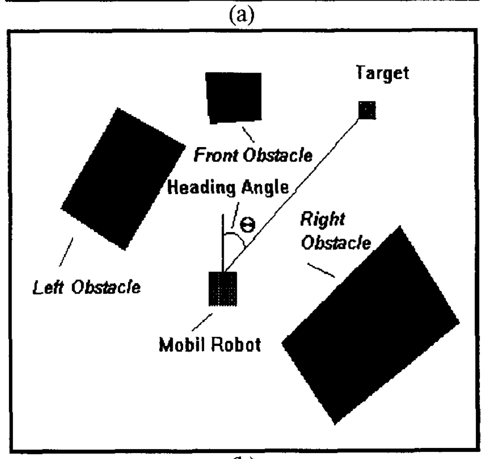
where the minimum values, *right_obs*, *front_obs*, and *left_obs*, derived from the sensor data d_i (i = 1, ..., 15), express the distances between the robot and obstacles to the right, front, and left locations, respectively.

The mobile robot is equipped with two wheel encode units to determine its current coordinates. At a start position, a counter is reset to zero. When the robot moves, its current coordinates can be roughly computed by counting the numbers of pulses from the wheel encodes that are attached on driving motors.

The THMR-II mobile robot with 1.0m lenght and 0.8m width is equipped with two driving wheels and one driven wheel. The velocities of the driving wheels are controlled by a motor drive unit.



(a)



(b)

Fig.3: Fuzzy logic scheme for perception-action behavior control

III. Fuzzy Logic Navigation Scheme

The input signals to fuzzy logic scheme are the 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.3a. When the target is located to the left side of the mobile robot, a heading angle *head_ang* is defined as negative; while 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.3b. According to acquired range information, reactive behaviors are weighted by 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 *right_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 fields, the distances between the robot and obstacles serve as a repulsive force for avoiding obstacle, while the heading angle serves as an attractive force for moving to target.

IV. Description Of Reactive Behaviors Using Fuzzy Logic

In order to reach a specified target in a complex environment, the mobile robot at least needs the following reactive behaviors: 1. Obstacle avoidance and decelerating at curved and narrow roads; 2. Following edges; 3. Target steer. Because the real world is a complex, using sensors it is very difficult to acquire precise information about dynamic environments. In this case, a set of fuzzy logic rules is used to describe the reactive behaviors mentioned above [13][14]. Now, we only list parts of fuzzy rules from the rule base to explain, in principle, how these reactive behaviors are realized (in fact, much more fuzzy rules have been used in our navigation algorithms).

A. Obstacle Avoidance and Decelerating at Curved and Narrow Roads

When the acquired information from the ultrasonic sensors shows that there exist obstacles nearby robot or the robot moves at curved and narrow roads, it must reduce its speed to avoid obstacles. In this case, its main reactive behavior is decelerating for obstacle avoidance. We give the first and second of fuzzy rules for realizing this behavior 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).

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

B. Following Edge

When the robot is moving to a specified target inside a room (Fig.1), it must reflect following edge behavior. The first and second rules for describing this behavior are listed as follows:

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).

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

C. Target Steer

When the acquired information from the ultrasonic sensors shows that there are no obstacles around robot, its main reactive behavior is target steer. Here, we list the first and second of fuzzy rules for realizing this behavior as follows:

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).

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.

V. Multiple Behaviors Fusion By Fuzzy Reasoning

A key issue of behavior-based control is how to efficiently coordinate conflicts and competitions among different reactive behaviors to achieve a good performance. In [1], a priority strategy is used to activate a reactive behavior according to its urgency level. This strategy is highly contentious for robot navigation in complex environments. For example, it is difficult to determine exactly which one of the reactive behaviors, *obstacle avoidance*, or *following edges*, or *target steer*, should be fired when the robot moves through the entrance of the U-shaped object to a target, as shown in Fig.1. To reach the given target, in fact, all the three reactive behaviors must be efficiently integrated. The following are some deficiencies of the priority strategy noted in our experiments:

1. Much effort must be made to test and to adjust some thresholds for firing reactive behaviors during

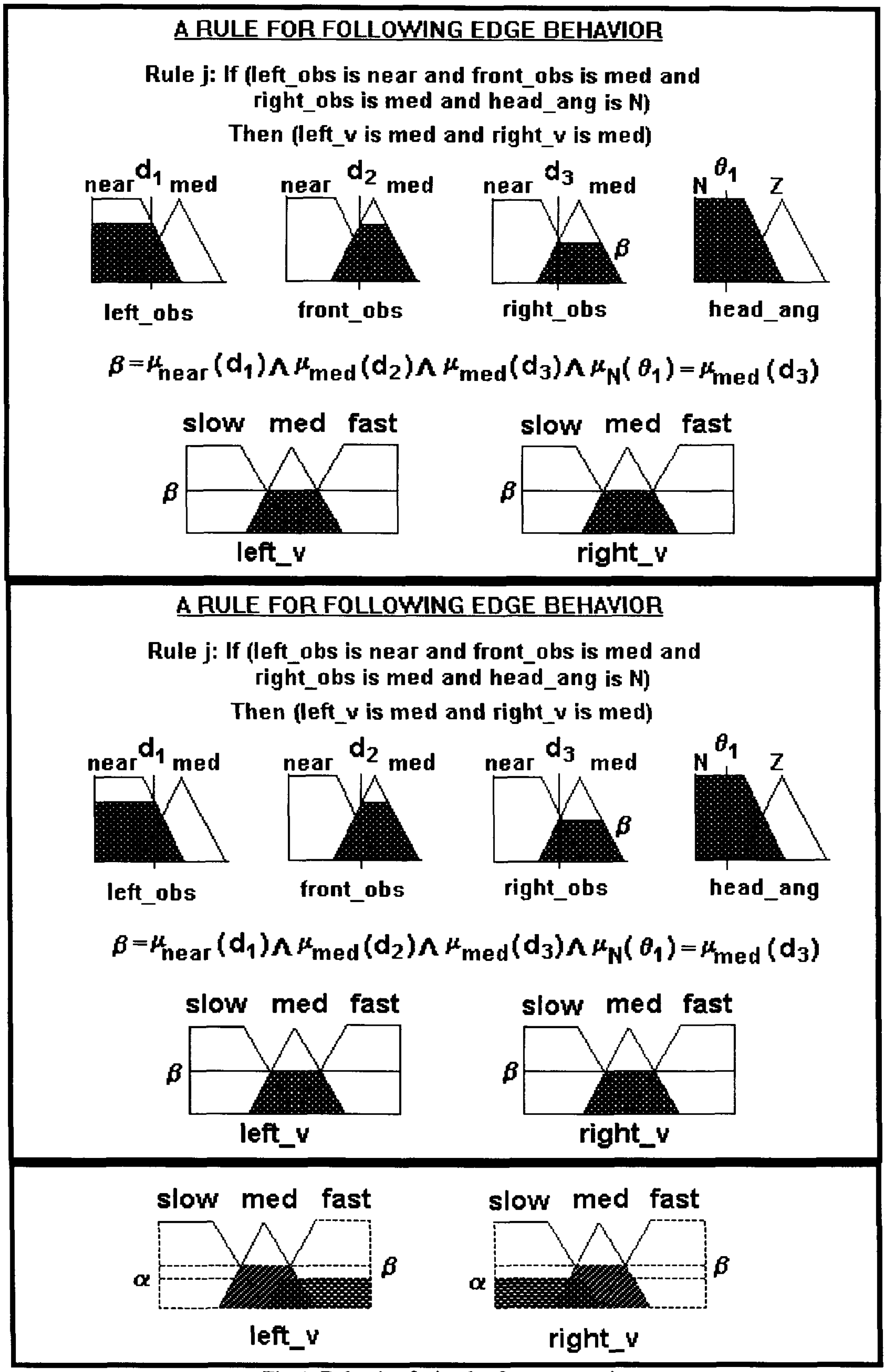


Fig.4: Behavior fusion by fuzzy reasoning

preprogramming.
2. These thresholds depend heavily on environments, i.e., a set of thresholds, determined in a given environment, may not be suitable for other environments.
3. Robot motion with unstable oscillations between different behaviors may occur in some cases. This is because just only one behavior could be activated at a given instant and two behaviors with neighboring priority, e.g., *obstacle avoidance* and *target steer*, are fired in turn.

In the proposed control strategy, reactive behaviors are formulated by fuzzy sets and fuzzy rules, and these fuzzy rules are integrated in one rule base. The coordination of different reactive behaviors can thus be easily performed by fuzzy reasoning. The following is an illustration of how this problem is dealt with by the Min-Max inference algorithm and the centroid defuzzification method in Eq.(1). For instance, the inputs, *left_obs*=d_1, *front_obs*=d_2, *right_obs*=d_3, *head_ang*=θ_1, are fuzzified by their membership functions to fire fuzzy rules associated with them simultaneously. Assume that *Rule i* (see below), formulating the *obstacle avoidance* behavior, and *Rule j* (see below), formulating the *following edge* behavior, are fired according to the fuzzified inputs (in fact, much more fuzzy rules may be activated):

Rule i : *If (left_obs is near and front_obs is near and right_obs is near and head_ang is N) Then (left_v is fast and right_v is slow).*
Rule j : *If (left_obs is near and front_obs is med and right_obs is med and head_ang is N) Then (left_v is med and right_v is med).*

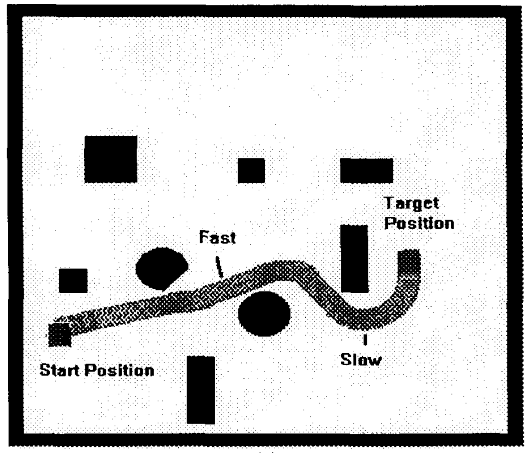
By fuzzy reasoning and the centroid defuzzification method, both *Rule i* and *Rule j*, related to the *obstacle avoidance* and *following edge* behaviors respectively, are weighted to determine an appropriate control action, i.e., the velocities, *left_v* and *right_v*, of the robot's rear wheels, as shown Fig.4.

VI. Simulations Of Robot Navigation Using Ultrasonic Sensors

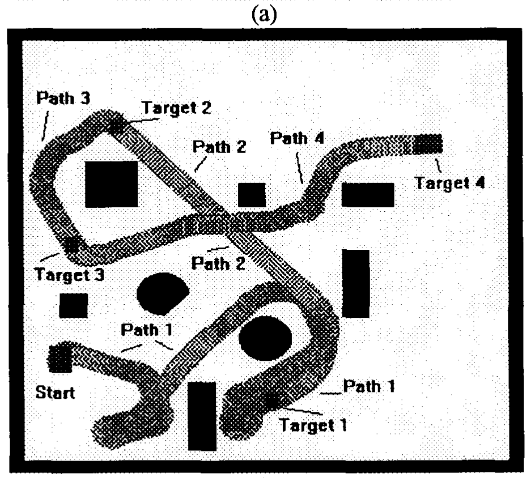
In this section we report several simulation results on robot navigation, only using ultrasonic sensors, in different environments.

A. Moving To 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 with 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 *moving to target* behavior and increasing the weight of *avoiding obstacle* and *following edge* behaviors. When the robot finds out the entry of the U-shaped object, it slowly reaches the target by reasonably integrating *avoiding obstacle* and *moving to target* behaviors.



(a)



(b)

Fig.5: Robot motion in a cluttered environment

B. Moving in a Cluttered Environment

Fig.5a-b shows robot motion in a cluttered environment. We choose at random several targets that are located among different obstacle distribution. Path 1 in Fig.5b represents robot motion from the start position to target 1 located in a narrow road; Path 2 in Fig.5b 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 start position is located. It can be observed that, only using ultrasonic sensors to acquire information about environments, the robot can successfully reach all targets by reasonably weighting more reactive behaviors using the proposed fuzzy logic navigation algorithm.

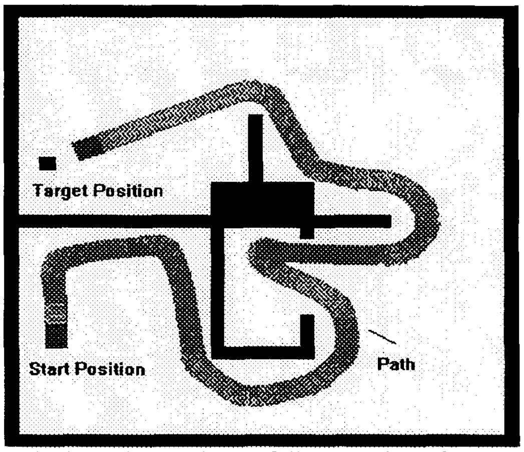


Fig.6: Robot motion by following edge behaviors

C. Following Wall Edges

In some applications, a mobile robot should be able to move from a room to another room. Fig.6 shows that a start position and a target position are located in different rooms. Using the fuzzy navigation algorithm, 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.

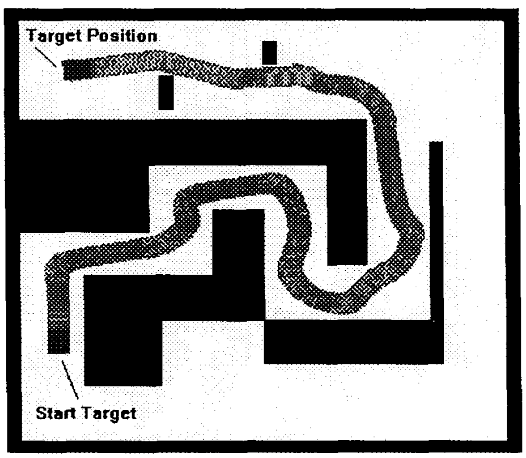


Fig.7: Robot motion with lower speed at curved and narrow roads

D. Decelerating at Curved and Narrow Roads

When the mobile robot operates in outdoor environments, it should be able to tack roads to reach a target. The example in Fig.7 shows robot navigation at curved and narrow roads. The robot begins from its start position and is automatically decelerating at the first curved road with 90°. Then it moves into a very narrow road with a slow speed. At the following curved roads with 90°, the robot automatically makes turns to keep on the roads. Finally, the robot gets the road where the target is located and move to the target with obstacle avoidance, using local information acquired by ultrasonic sensor and the heading angle between the robot and the target.

VII. Vision System

The simulation results show that the proposed method, only using ultrasonic sensors, can perform robot navigation in complex and uncertain environments by weighting multiple reactive behaviors, such as avoiding obstacles, decelerating at curved and narrow roads, and moving to target and so on. However, only ultrasonic sensors do not guarantee to provide a good path for robot navigation (in Fig.5b) in some case since complete information on enivironments is not available. Here, a vision system is used to improve navigation performance. This vision system consists of a TV camera and an image processing unit [10]. This unit analyzes the image data to recognize the distribution of obstacles in local region. According to information on the obstacles' distribution, the robot identifies some subgoals for determining a good motion direction to avoid robot trap in local region. Fig.8a shows robot motion from a start position to target position by following right edge behavior. A trap motion occurs during robot navigation due to a U-shaped object. To avoid the trap motion, the vision system identifies a subgoal to determine a good motion direction, as shown in Fig.8b.

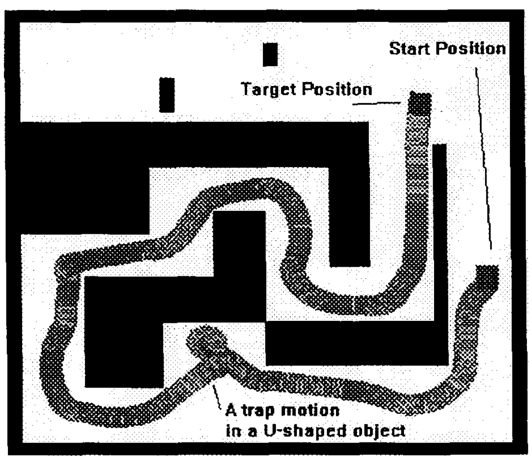


Fig.8a: Navigation by ultrasonic sensors

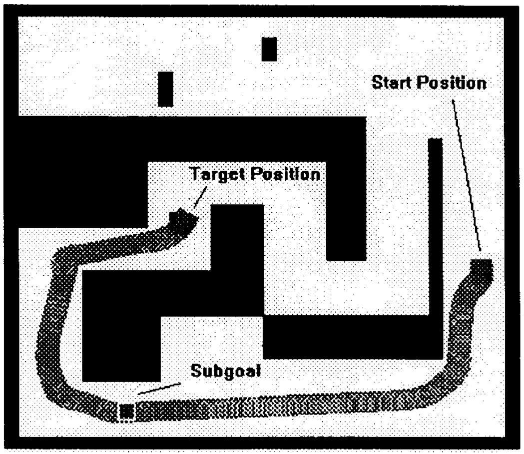


Fig.8b: Navigation by multisensor integration

VIII. CONCLUSIONS

In this paper, we use fuzzy logic to realize the reactive behaviors for robot navigation. The method can effectively coordinate conflicts and competitions among multiple reactive behaviors by weighting them and this coordination ability is nearly independent of a dynamic environment due to it robustness. The navigation algorithm has better reliability and real-time response since perception and decision units in the algorithm are integrated in one module and are directly oriented to a dynamic environment. The simulation results show that the proposed method for robot navigation by multisensor integration can automatically perform avoiding obstacles, decelerating at curved and narrow roads, escaping from a U-shaped object, and moving to target and so on in complex and uncertain environments.

REFERENCES

[1] R.A. Brooks, "A robust layered control system for a mobile robot", *IEEE J. of Robotics and Automation*, RA-2, pp. 14-23, April 1986.

[2] Ronald C. Arkin, and Robin R. Murphy, "Autonomous navigation in a manufacturing environment", *IEEE Tran. on Robotics and Automation*, vol.6, no.4, pp.445-454, 1990.

[3] M.D. Adams, Housheng Hu and P.J. Probort, "Towards a real-time architecture for obstacle avoidance and path planning in mobile robot", *Proc. IEEE Int. Conf. on Robotics and automation*, pp.584-589, March 1990.

[4] B.H. Krogh, "A generalized potential field approach to obstacle avoidance control", SME-RI Technical Paper MS84-484, 1984.

[5] O. Khatib, "Real-time obstacle avoidance for manipulators and automobile robots", *Int. J. of Robotics Research*, vol.5, no.1, 1986.

[6] Xun Feng, "Potential field based behavior control of mobile robot", Technical Report, Department of Computer Science, Tsinghua University, 1993, unpublished.

[7] Wei Li: "Fuzzy logic based 'perception action' behavior control of an mobile robot in uncertain environments" *IEEE World Congress On Computational Intelligence*, in press, 1994.

[8] Wei Li: "perception action behavior control of a mobile robot in uncertain environments using fuzzy logic". *IEEE/RSJ International Conference On Intelligent Robots and Systems*, in press, 1994.

[9] M. Sugeno and M. Nishida, "Fuzzy control of model car", *Fuzzy Sets and Systems*, vol.16, pp.103-113, 1985.

[10] T. Takeuchi; Y. Nagai and N. Enomoto, "Fuzzy control of a mobil robot for obstacle avoidance", *Information Science*, vol.45, pp.231-248, 1988.

[11] M. Maeda; Y.Maeda and S. Murakami, "Fuzzy drive control of an autonomous mobile robot", *Fuzzy Sets and Systems*, vol.39, pp.195-204, 1991.

[12] Wei Li and Kezhong He: "Sensor-based robot navigation in uncertain environments using fuzzy controller" *The 1994 ASME International Computers in Engineering Conference*, in press, 1994.

[13] Wei Li: "Fuzzy logic based reactive behavior control of an autonomous mobile system in unknown environments" *International Journal of Engineering Application of Artificial Intelligence*, Pergamon Press, in press, 1994.

[14] Wei Li and X. Feng.: "Behavior fusion for robot navigation in uncertain environments using fuzzy logic", *The 1994 IEEE International Conference on Systems, Man and Cybernetics*, in press, 1994.