Intelligent fuzzy interface technique for the control of an autonomous mobile robot

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Abstract: In this article, research has been carried out on the control technique of an autonomous mobile robot to navigate in a real-world environment, avoiding structured and unstructured obstacles, especially in a crowded and unpredictably changing environment. Here a successful way of structuring the navigation task, dealing with the issues of individual robot behaviours, is discussed. Action coordination of the behaviours has been addressed using fuzzy logic in the present research. The inputs to the proposed fuzzy-control scheme consist of a heading angle between a robot and a specified target, and the distances between the robot and the obstacles to the left, front, and right of its locations, being acquired by an array of sensors. The proposed intelligent controller for mobile robot navigation algorithm employing fuzzy theory has been applied in a complex environment. The results are verified in simulation and experimental modes, which are in good agreement.

Keywords: navigation, dynamic environment, fuzzy logic, autonomous robots

1 INTRODUCTION

Intelligent control of a mobile robot is one of the challenging tasks among the researchers and scientists throughout the world. Therefore, the current research and development of mobile robots have attracted the attention of researchers in the areas of engineering, computer science, biology, mining, and others. This is due to the high application potential of mobile robots. Autonomous mobile robots are intelligent agents that can perform desired tasks in unstructured environments without continuous human guidance [**1–4**]. Many kinds of robots are autonomous to some degree. One important area of current robotics research is to enable the robot to cope with its environment whether this is on land, underwater, in the air, underground, or in space. A fully autonomous robot in the real world has the ability to:

(a) gain information about the environment;
(b) travel from one point to another point, without human navigation assistance;
(c) avoid situations that are harmful to people, property, or itself;
(d) repair itself without outside assistance.

A robot may also be able to learn autonomously. Autonomous learning includes the ability to:

(a) learn or gain new capabilities without outside assistance;
(b) adjust strategies based on the surroundings;
(c) adapt to surroundings without outside assistance.

Navigation for mobile robots can be well-defined in mathematical (geometrical) terms. It also involves many distinct sensory inputs and computational processes. Elementary decisions such as turn left, or turn right, or run or stop are made on the basis of thousands of incoming signals [**5–7**]. Thus, it is necessary to define what navigation is and what the function of a navigation system is. Navigation is traditionally defined as the process of determining and maintaining

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a trajectory to a goal location [**6**]. Biological navigation behaviours have been an important source of inspiration for robotics in the past decade. According to Levitt and Lawton [**8**], navigation consists of answering three questions: (a) 'Where am I?'; (b)'Where are other places with respect to me?'; and (c) 'How do I get to other places from here?' However, biological systems do not necessarily require all that knowledge to navigate, but they usually work on a 'how do I reach the goal?' basis. Most systems typically deal with different degrees of knowledge depending on the circumstances.

Humans have a remarkable capability to perform a wide variety of physical and mental tasks without any explicit measurements or computations. Examples of everyday tasks are parking a car, driving in city traffic, playing golf, cooking a meal, and summarizing a story. In performing such familiar tasks, humans use perceptions of time, distance, speed, shape, and other attributes of physical and mental objects [**9**]. The theory of fuzzy logic systems (FLS) is inspired by the remarkable human capability to operate on and reason with perception-based information. Rule-based fuzzy logic provides a scientific formalism for reasoning and decision-making with uncertain and imprecise information. The main advantages of a fuzzy navigation strategy lie in the ability to extract heuristic rules from human experience and to obviate the need for an analytical model of the process [**10**].

A new intelligent fuzzy interface system has been developed in this current investigation. The FLS developed for controlling the robot has inputs from various sensors. Sensor signals are fed to the FLS, and the output provides motor control commands (e.g. turn right or left). The FLS learns the full dynamics of the mobile robot online. Each fuzzy controller for the mobile robot has four inputs and two outputs. Both inputs and outputs have three membership functions. Each membership function is considered as a combination of trapezoidal and triangular membership function. This research focuses on a fuzzy logic framework to be implemented in the mobile robot for behaviour design and coordination. The results are verified in the simulated and real-world tests. A general control system of an autonomous mobile robot that can navigate to a desired location in a known and an unknown environment has been exhibited in Fig. 1. Localization map and cognition path planning are the subsystems of the fuzzy inference technique module as shown in Fig. 1. These two subsystems are incorporated and visualized in the fuzzy system as various fuzzy rule sets. The input to the fuzzy system is a perception module and the output is a motion-control module. This fuzzy interface system for controlling the robot has been authenticated by experimental verification. This article is organized as follows. In section 2, fuzzy logic behaviour for control technique has been discussed. Simulation results are summarized in section 3. Finally, in section 4 the experimental results are discussed and compared in terms of performance and effectiveness of the controller.

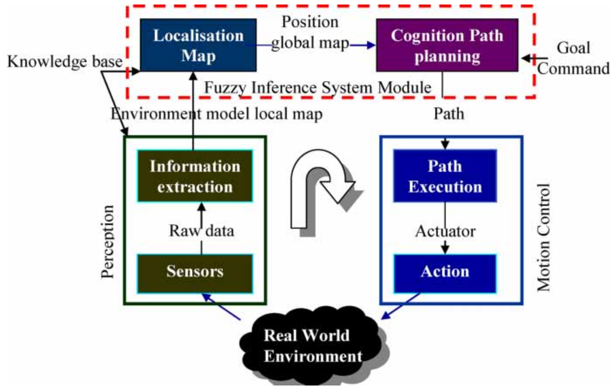

Fig. 1 General control scheme of an autonomous mobile robot

2 FUZZY LOGIC BEHAVIOUR FOR CONTROL TECHNIQUE

The first and most common application of fuzzy logic techniques in the domain of an autonomous mobile robot is the use of fuzzy control to implement individual behaviour units. Fuzzy logic controllers incorporate heuristic control knowledge in the form of *if-then* rules and are a convenient choice when a precise linear model of the system to be controlled cannot be easily obtained. Fuzzy logic has features that are particularly attractive in light of the problems posed by an autonomous robot navigation. Fuzzy logic allows the modelling of different types of uncertainty and imprecision, building robust controllers starting from heuristic and qualitative models, and integrating symbolic reasoning and numeric computation in a natural framework [**11**].

An intelligent controller for a mobile robot enables the robot to avoid the obstacle and improve target-seeking ability. The inputs to the proposed fuzzy-control scheme consist of a heading angle between a robot and a specified target, and the distances between a robot and the obstacles to the left, front, and right locations, acquired by an array of sensors. The outputs from the control scheme are commands for the speed-control unit of two side wheels of the mobile robot. The input signals to the fuzzy navigation algorithm are the distances between the robot and the obstacles to the left, front, and right locations, as well as the heading angle between the robot and a specified target, as shown in Fig. 2. When the target is located at the left and right sides of the mobile robot, heading angles are negative and positive, respectively [**12**].

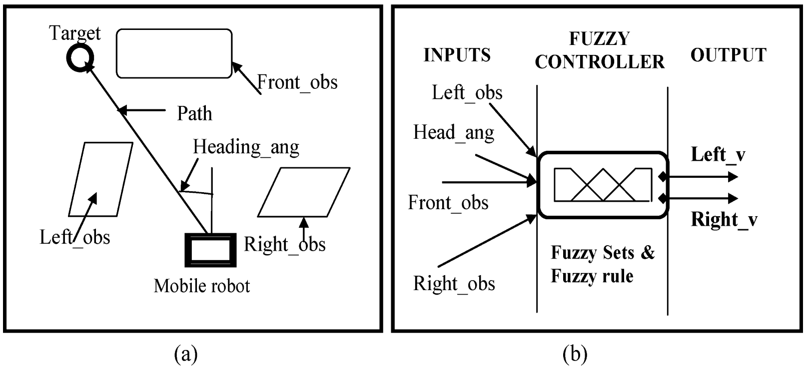

Fig. 2 Fuzzy logic techniques for behaviour-based control of mobile robot

According to the acquired range information by sensors, reactive behaviours are weighted by the fuzzy logic algorithm to control the velocities of the two driving wheels of the robot. The basic configuration of a fuzzy system consists of four principal elements: fuzzifier, fuzzy rule base, fuzzy inference engine, and defuzzifier. The fuzzifier is a mapping from the observed crisp input space to the fuzzy sets defined in; the defined fuzzy set is characterized by a membership function and is labelled by linguistic variables near, medium, and far, and these are chosen to fuzzify left_obs, right_obs, and front_obs. The linguistic variables *P* (positive), *Z* (zero), and *N* (negative) are used to fuzzify head_ang and the linguistic variables slow, med, and fast (Table 1). These are used to fuzzify the velocities of the left_v and right_v, respectively [**13**].

The fuzzy rule base is a set of linguistic rules in the form of '*if* a set of conditions are satisfied, *then* a set of consequences are inferred'. For four inputs and two outputs fuzzy system, the general fuzzy rule base may consist of the following.

If (matching degree of x_1 is $\mu(x_1)$ *and* matching degree of x_2 is $\mu(x_2)$ *and* matching degree of x_3 is $\mu(x_3)$ *and* matching degree of x_4 is $\mu(x_4)$), *Then* (matching degree of v_l is $\mu(y_i)_\mathrm{l}$ *and* matching degree of v_r is $\mu(y_i)_\mathrm{r}$).

The matching degree of final output is computed by the following formula

$$\text{Matching degree } \mu(y_i)_{\mathrm{l,r}} = \min\{\mu(x_1), \mu(x_2)\\ \mu(x_3), \text{and } \mu(x_4)\}$$

where $i = (1, 2, 3, \ldots, n)$; $x_1, x_2, x_3, x_4 =$ are the sensor inputs of left, right, front obstacle distance, and heading angle, respectively; $\mu(x_1)$, $\mu(x_2)$, $\mu(x_3)$, $\mu(x_4)$ the matching degrees of corresponding sensor inputs; v_l, $v_\mathrm{r} =$ the velocities of the left and right wheels respectively; $\mu(y_i)_\mathrm{l}$, $\mu(y_i)_\mathrm{r}$ the inferred input matching degrees of corresponding left and right wheel velocities respectively.

When the matching degree $= 1$ the inferred conclusion is identical to the rule's consequent, and if it is zero no conclusion can be inferred from the rule.

Finally, the output firing area of the left and right wheel velocities can be computed by the following formula

$$\mu_\mathrm{A}(y_i)_{\mathrm{l,r}} = \max\{\mu(x_1), \mu(x_2), \mu(x_3), \text{and} \mu(x_4)\}$$

The final output (crisp value) of the fuzzy logic controller of left and right wheel velocities can be calculated by

$$\text{Left and right wheel velocities} = w_{1,\mathrm{r}} = \frac{\sum_{i=1}^{n} \mu_A(Y_i) \times (V_i)}{\sum_{i=1}^{n} \mu_A(Y_i)}$$

where $\mu_\mathrm{A}(y_i)_{\mathrm{l,r}}$ is the firing area of the left and right wheel velocities for the *i*th rule, V_i the centroid distance of the area, and *n* the total number of parameter.

To reach a specified target in a complex environment, the mobile robot needs at least the following reactive behaviours: (a) obstacle avoidance and target seeking, (b) following edges, and (c) target steer. In this

Table 1 Parameter for variables

Left obstacle distance (left_obs) Right obstacle distance (right_obs) Front obstacle distance (front_obs)	Near (M) 0.0–0.6	Medium (M) 0.6–0.9	Far (M) 0.9–1.2
Heading angle (head_ang)	Negative −60° to 0°	Zero −30° to +30°	Positive 0°–60°
Left wheel velocity (left_v) Right wheel velocity (right_v)	Slow (m/s) 0–2	Medium (m/s) 1–2	Fast (m/s) 2–4

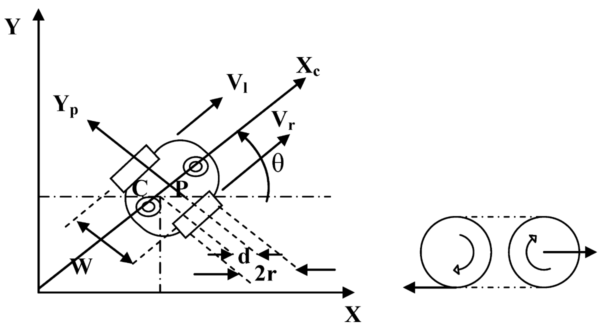

Fig. 3 Kinematics of mobile robot

case, a set of fuzzy logic rules is used to describe the reactive behaviours as mentioned above. Now, the last part of fuzzy rules from the rule base is to explain, in principle, how these reactive behaviours are realized.

2.1 Robot behaviour

Each robot has four wheels (Fig. 3): two front supported wheels that are free and two side middle wheels that are powered by separate servo motors. Each robot has an array of infrared sensors for measuring the distances of obstacles around it, an infrared sensor for detecting the bearing of the target, and a radio system for communicating with other robots. The information being sent among the robots are (a) their positions, (b) how far they are from the target, and (c) whether reached the target or not. According to the information acquired by the robots using their sensors, some of the fuzzy control rules are activated. The outputs of the activated rules are combined by fuzzy logic operations to control the velocities of the driving wheels of the robots. These are denoted by left_v and right_v, for the velocity of the left wheel and right wheel of each robot, respectively. The above membership functions are triangular or trapezoidal and the parameters defining the function are listed as shown in Fig. 4; these parameters can be used to generate different fuzzy rules, for example

Rule

If (left_obs is far *and* right_obs is medium, *and* front_obs is near *and* head_ang is *N*), *Then* (left_v is slow *and* right_v is medium).

By fuzzy reasoning and the centroid defuzzification method, the rule related to the obstacle-avoidance, wall-following, and target-seeking behaviours is weighted to determine an appropriate control action, i.e. the velocities, left_v and right_v, of the robot's side wheels as shown in Fig. 5, and the values of the parameters are decided empirically.

2.2 Obstacle avoidance

When a robot is close to an obstacle, it must change its speed and steering angle to avoid the obstacle. Mobile robot is able to avoid static as well as dynamic obstacle. If more than one robot is present in the environment, then a robot treats other robots as dynamic obstacles (Fig. 6). The fuzzy rules used for obstacle avoidance and motion control by the robots are listed in Table 2 as rules 1–27. All the rules in the table are obtained heuristically. Figure 5 shows a typical fuzzy controller scenario for obstacle avoidance.

When the robot senses an obstacle near to it or when it moves on curved and narrow roads, it must reduce its speed to avoid collision. In this case, its main reactive behaviour is decelerating for obstacle avoidance. This gives the first and second of fuzzy logic rules for realizing this behaviour as follows.

If (left_obs is near *and* right_obs is near *and* front_obs is near *and* head_ang is any), *Then* (left_v is slow *and* right_v is fast).

If (left_obs is near *and* right_obs is near *and* front_obs is medium *and* head_ang is any), *Then* (left_v is slow *and* right_v is slow).

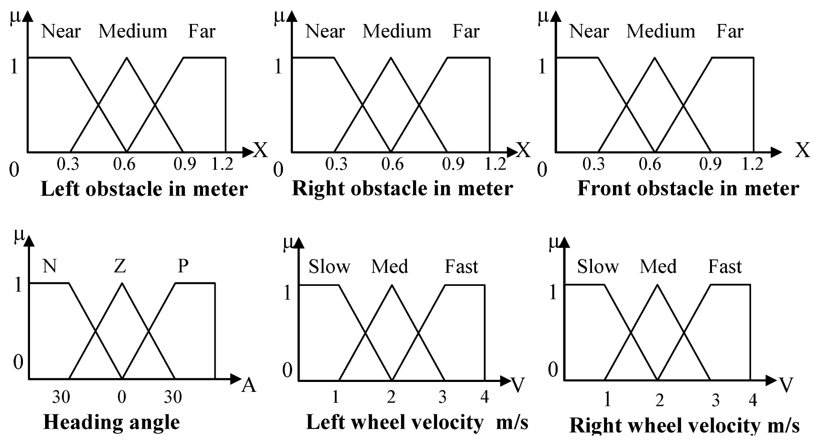

Fig. 4 Fuzzy membership function

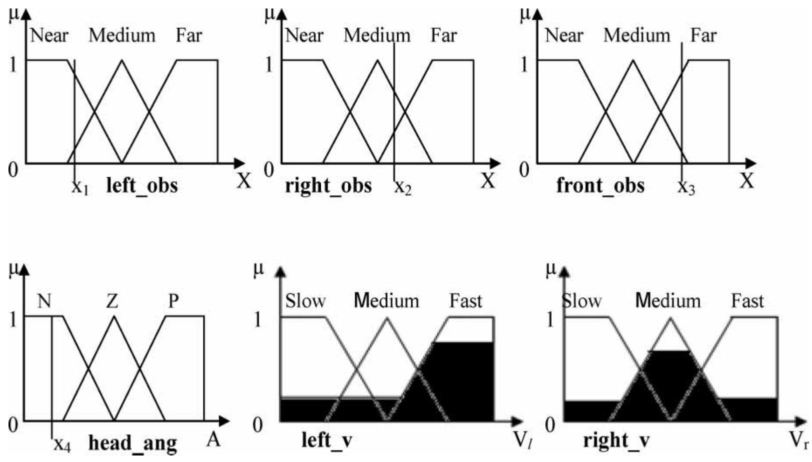

Fig. 5 Schematic diagram of the fuzzy logic for navigation of mobile robots

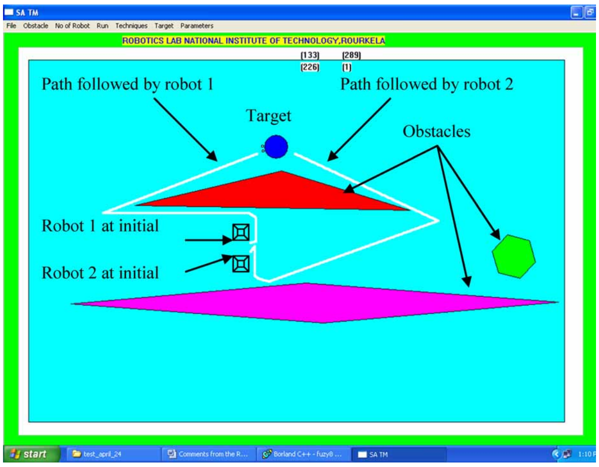

Fig. 6 Static as well as dynamic obstacle avoidance

Such fuzzy rules represent that the robot pays attention only to obstacle avoidance (Fig. 7) and moves accordingly to the rule listed in Table 2 when it is close to obstacles or at curved and narrow roads.

2.3 Wall-following behaviour

When the robot is moving to a specified target through a narrow channel, or escaping from a U-shaped wall or dead-end obstacle (Figs 8 and 9), specific fuzzy rules for wall-following behaviour (Table 3) are activated. In the absence of the wall-following behaviour, the robot is incapable of reaching the goal position when it encounters U-shaped or dead-end obstacles on their path. In such a situation, the robot should keep on heading towards the goal position. But when it moves towards the goal position, it also comes closer to the obstacles. Any obstacle-avoidance behaviour except wall-following behaviour would make the robot divert from its goal position.

For rules 28 and 29, the antecedent and consequent will be:

If (left_obs is far *and* right_obs is far *and* front_obs is near *and* head_ang is any), *Then* (left_v is med *and* right_v is slow).

If (left_obs is far *and* right_obs is medium *and* front_obs is near *and* head_ang is any), *Then* (left_v is slow *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 right or left of the robot, and the target is also located at the right or the left. The wall-following behaviour depends on a heading angle between the robot and a specified target.

2.4 Target-seeking behaviour

When the acquired information from the sensors shows that there are no obstacles around the robot, its main reactive behaviour is target steer. The simulation result for target steer and map localization is shown in Fig. 10, by following the rule from Table 4 (i.e. rules 34 and 35).

If (left_obs is far *and* right_obs is far *and* front_obs is far *and* head_ang is *P*), *Then* (left_v is fast *and* right_v is med).

If (left_obs is far *and* right_obs is far *and* front_obs is medium *and* head_ang is *N*), *Then* (left_v is med *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. Generally, the weights of the behaviours, obstacle avoidance, and target steer depend largely on the distances between the robot and the obstacles to the left, front, and right locations. When the robot reaches

Table 2 Parameter for variables

Rule no.	Action	Left_obs	Right_obs	Front_obs	Head_ang	Left_v	Right_v
1	AO	Near	Near	Near	Any	Slow	Fast
2	AO	Near	Near	Medium	Any	Slow	Slow
3	AO	Near	Near	Far	Any	Med	Med
4	AO	Near	Medium	Near	Any	Med	Slow
5	AO	Near	Medium	Medium	Any	Med	Slow
6	AO	Near	Medium	Far	Any	Fast	Med
7	AO	Near	Far	Near	Any	Fast	Slow
8	AO	Near	Far	Medium	Any	Med	Slow
9	AO	Near	Far	Far	Any	Fast	Med
10	AO	Medium	Medium	Near	Any	Fast	Slow
11	AO	Medium	Medium	Medium	Any	Slow	Slow
12	AO	Medium	Medium	Far	Any	Fast	Fast
13	AO	Medium	Near	Near	Any	Slow	Fast
14	AO	Medium	Near	Medium	Any	Slow	Med
15	AO	Medium	Near	Far	Any	Slow	Med
16	AO	Medium	Far	Near	Any	Med	Slow
17	AO	Medium	Far	Medium	Any	Med	Fast
18	AO	Medium	Far	Far	Any	Fast	Med
19	AO	Far	Near	Near	Any	Slow	Med
20	AO	Far	Near	Medium	Any	Med	Fast
21	AO	Far	Near	Far	Any	Med	Fast
22	AO	Far	Medium	Near	Any	Slow	Fast
23	AO	Far	Medium	Medium	Any	Slow	Med
24	AO	Far	Medium	Far	Any	Med	Fast
25	AO	Far	Far	Near	Any	Fast	Slow
26	AO	Far	Far	Medium	Any	Fast	Med
27	AO	Far	Far	Far	Any	Fast	Fast

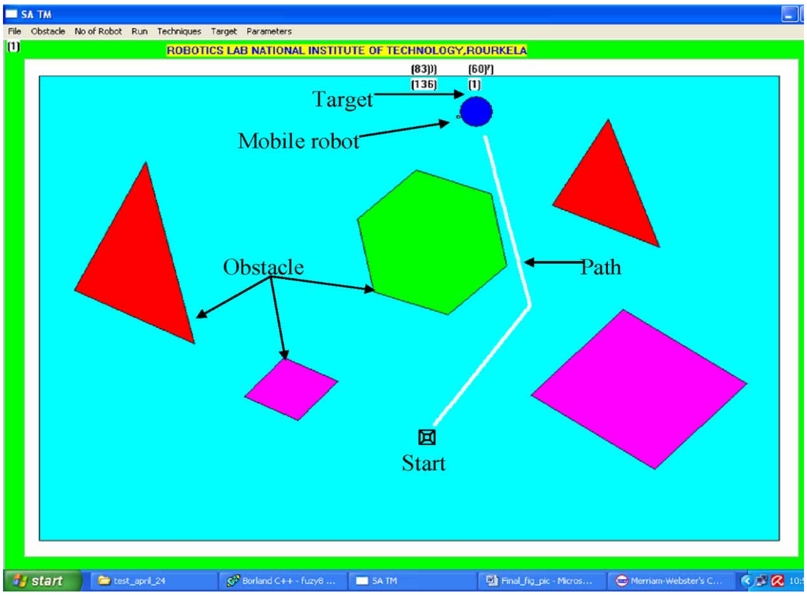

Fig. 7 Obstacle-avoidance and motion-control behaviours

the local target, it stops and waits for the other robot to reach the target for further coordinated action at their end. The position of the robots is communicated between each other in the perception model through radio modems. By this communication each robot knows the position of other robots present in that environment. When the robot gets lost, it tries to make contact with other robots and those robots try to locate the lost robot by a coordinated action. If a robot is lost, it tries to undo its movement till it is within the preview of other robots present in that environmental scenario.

3 SIMULATION RESULTS AND DISCUSSION

In most of the literatures, the simulation study is carried out for path-tracking [**13**], goal-finding, and

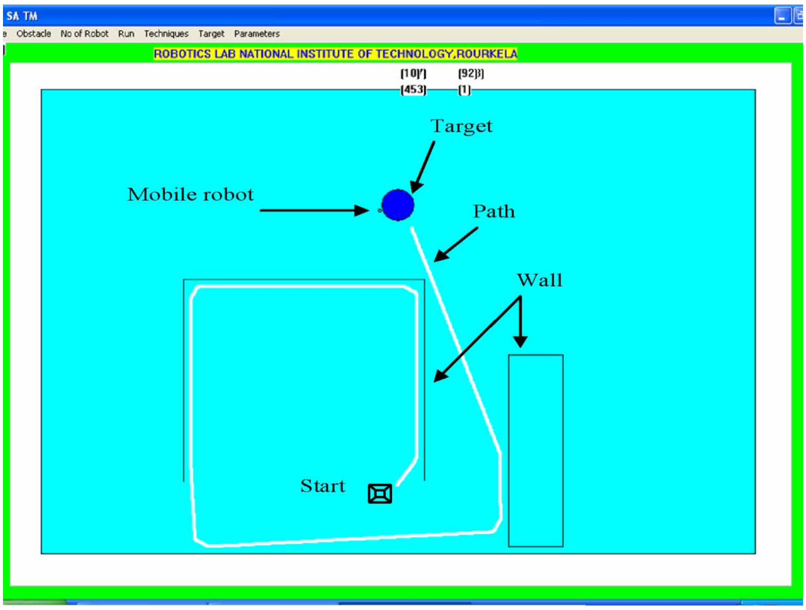

Fig. 8 Wall-following behaviour

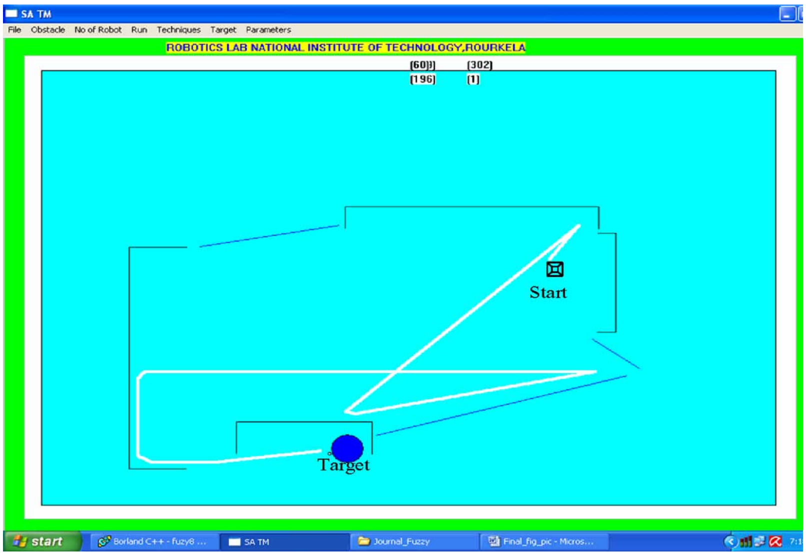

Fig. 9 Escape from dead ends and find the target

Table 3 List of rules for wall-following behaviour

Rule No.	Action	Left_obs	Right_obs	Front_obs	Head_ang	Left_v	Right_v
28	FE	Far	Far	Near	Any	Med	Slow
29	FE	Far	Medium	Near	Any	Slow	Med
31	FE	Medium	Far	Near	Any	Fast	Med
31	FE	Near	Far	Medium	Any	Fast	Med
32	FE	Near	Far	Near	Any	Fast	Med
33	FE	Near	Medium	Far	Any	Med	Slow

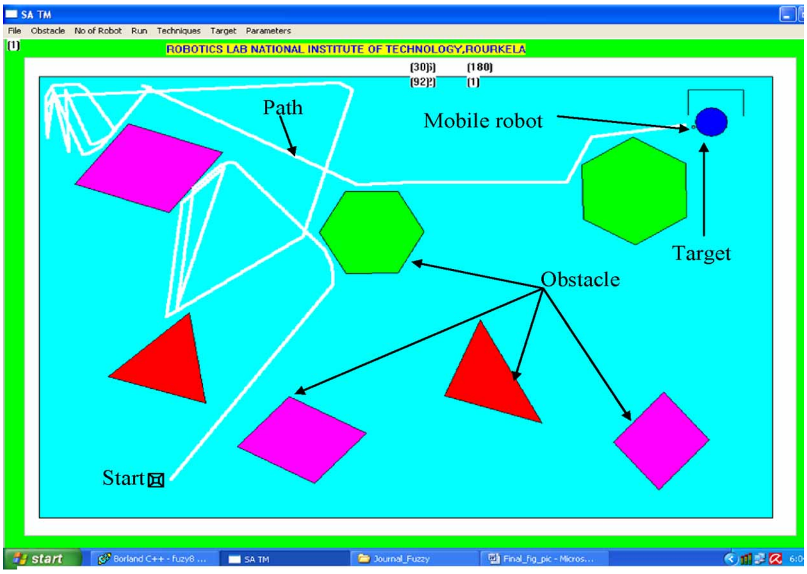

Fig. 10 Target-seeking and map-localization behaviours

Table 4 List of rules for target-seeking and map-localization

Rule No.	Action	Left_obs	Right_obs	Front_obs	Head_ang	Left_V	Right_V
34	TS	Far	Far	Far	*P*	Fast	Med
35	TS	Far	Far	Medium	*N*	Med	Fast
36	TS	Far	Far	Far	*Z*	Fast	Fast
37	TS	Far	Far	Medium	*P*	Slow	Med
38	TS	Far	Medium	Far	*N*	Med	Fast
40	TS	Medium	Far	Far	*Z*	Fast	Fast

avoid-static obstacle only [**14**]. In this article, a new intelligent controller has been proposed for mobile robot navigation using fuzzy logic. It is more efficient than traditional reactive behaviour control using artificial potential fields, as used by Arkin [**14**]. The navigation algorithm has better reliability and real-time response because perception, localization, cognition, and motion-control decision units are integrated in one module and are directly oriented to a dynamic environment. The simulation results show that the proposed method, using information acquired by infrared sensors, can perform robot navigation in complex and uncertain environments.

The simulations were conducted with the ROBNAV software being developed in the laboratory using C++ [**15**]. Figure 11 shows a typical screen of the software. It can be noted that, in addition to the fuzzy logic-based navigation, the software also allows other navigation control. To demonstrate the effectiveness and robustness of the proposed method, simulation results on mobile robot navigation are exhibited in various environments.

The static as well as dynamic obstacle-avoidance behaviour is activated when the readings from any sensors are less than the minimum threshold values. This is how the robot determines if an object is close for a collision. When an object is detected too close to the robot, it avoids a collision by moving away from it in the opposite direction. Collision avoidance has the highest priority, and therefore it can override other behaviours, in this case, its main reactive behaviour is decelerating for obstacle avoidance as shown in Figs 6 and 7.

When the robot moves through a large U-shaped obstacle, at the initial stage, it runs directly towards the target, since the obstacles sensed are far away from it. Then, it makes a left turn, to avoid the obstacles at the direct front. As the target is located at the right side of the robot, the behaviour of the approaching target tries to make it turn to the right. As a result, it moves into the right, and the target orientation increases gradually. When the robot reaches the right side it tries to avoid obstacles (the right wall) and approach the target, so it turns to the left. On the basis of the preceding analysis, it will return to the left side. Consequently, the robot travels along the indefinite loop in this concave trap as shown in Fig. 12. To avoid this loop, the robot must have the wall-following behaviour. When the robot is moving to a specified target through a U-shaped obstacle or narrow channel, it must reflect

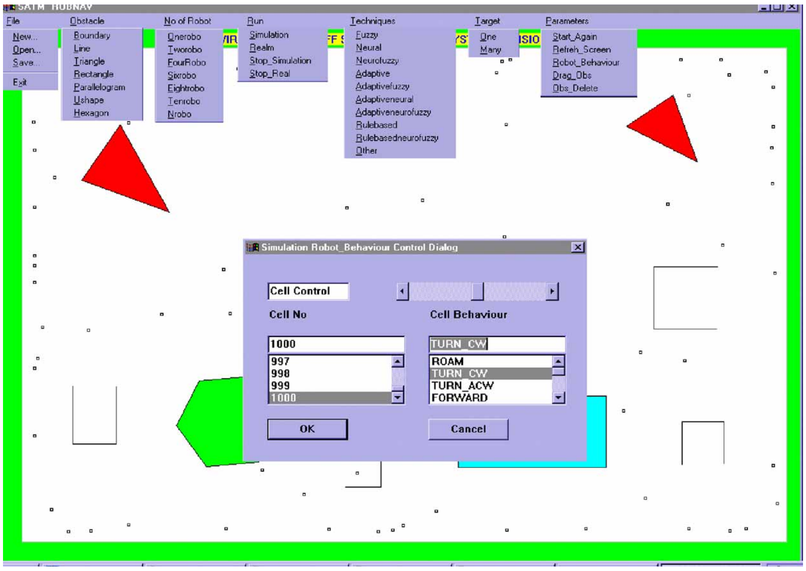

Fig. 11 Robot navigation software package (ROBNAV)

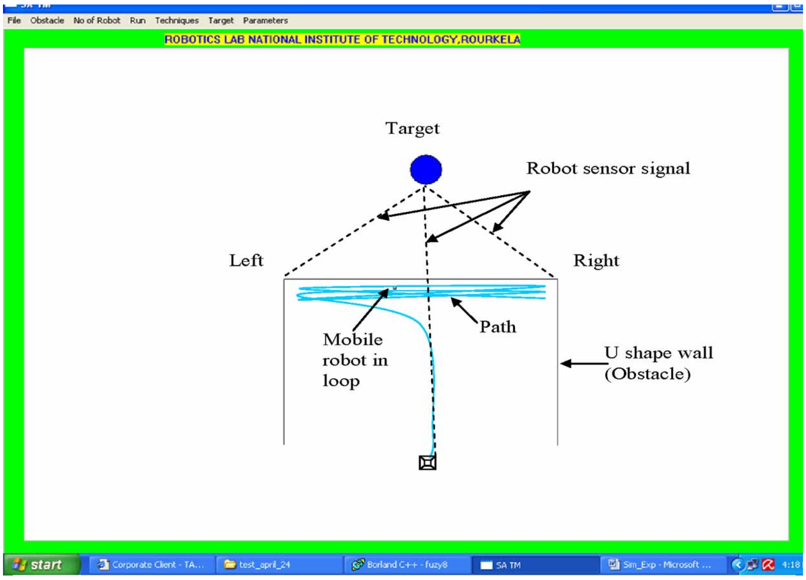

Fig. 12 Robot in indefinite loop in concave trap

following edge behaviour so that it may locate, find, and reach the specified target as shown in Fig. 8, and escape from dead end as shown in Fig. 9.

When the acquired information from the sensors shows that there are no obstacles around the robot, its main reactive behaviour is target steer. The intelligent controller mainly adjusts the robot's motion direction and quickly moves it towards the target if there are no obstacles around it, as shown in Fig. 10. In the proposed control strategy, reactive behaviours are formulated by fuzzy sets and fuzzy rules, and these fuzzy rules are integrated in one rule base.

4 EXPERIMENTAL RESULTS

The previously published paper by Das and Kar [**13**] has proposed an adaptive controller for a non-holonomic mobile robot to track the elliptical path only, and a comparison is made between the Arkin's [**14**] result and the result obtained from the current investigation during obstacle avoidance. It is found that the developed fuzzy controller can negotiate the obstacles as efficiently, as the artificial potential field method (Fig. 13). Moreover, the developed controller can be used for several mobile robots

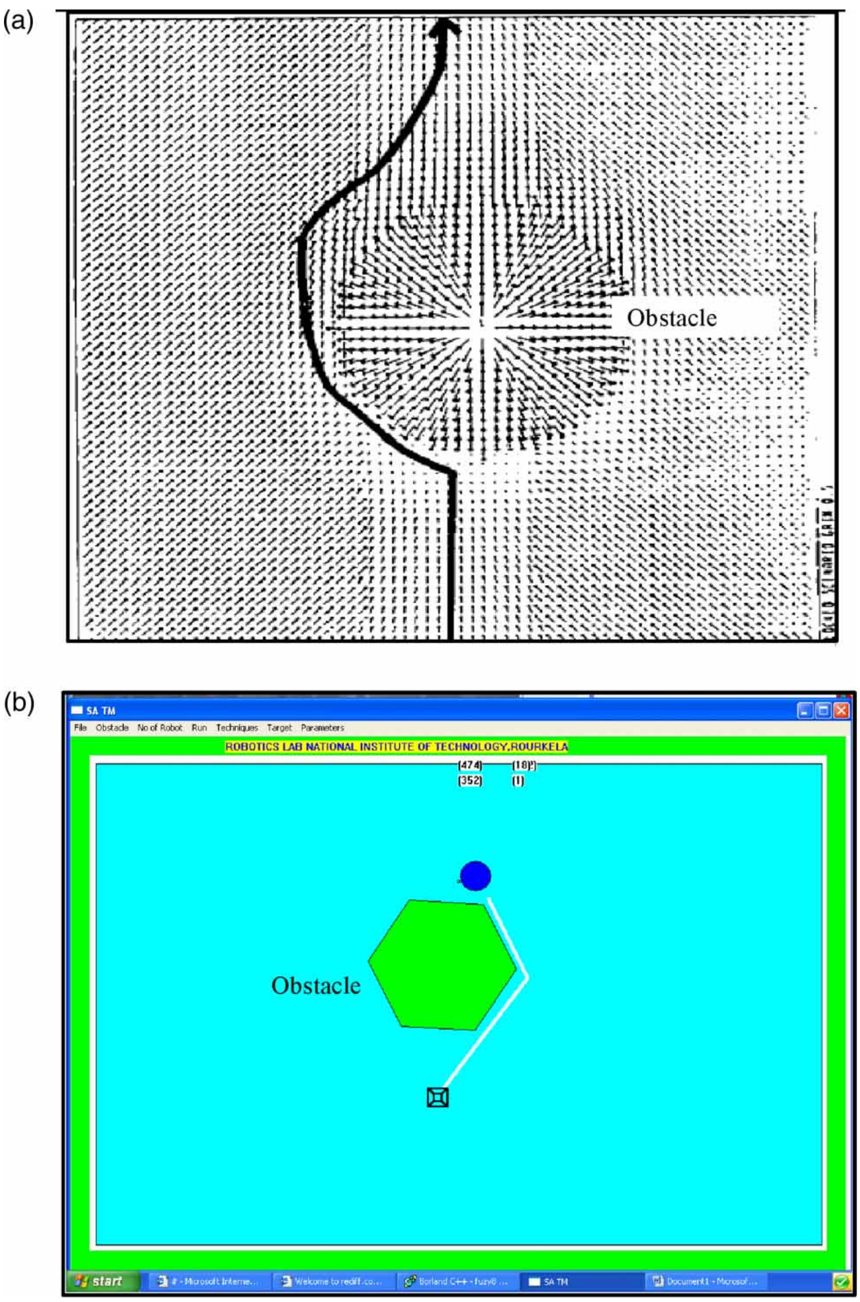

Fig. 13 Comparison of results during obstacle avoidance. Path traced by the robot embedded with (a) Arkin's [**14**] controller and (b) the developed fuzzy controller

(Fig. 6), negotiating both static and dynamic obstacles, whereas the Arkin's motor schema may only be used for single mobile robot navigation and avoid static obstacles. Fuzzy logic has features that are particularly attractive in light of the problems posed by an autonomous robot navigation.

Figure 14 shows the mobile robot developed in the robotics laboratory. The wheels of the robot have a radius of 3.5 cm and are mounted on an axle of length 18.0 cm. The chassis of the robot measures $16 \times 18 \times 15$ cm ($L \times W \times H$) and contains two DC gear servo motors, two supported free wheels for balance, transmission elements, and a 12 V battery. The wheels are driven by motors having rated torque 7 mN.m at 30 r/min and at 12-rated voltage. The assumptions about the mechanical structure and motion of a mobile robot, to which the proposed method is applied, are as follows.

(1) Mobile robot consists of rigid base fitted with DC gear servo motor and wheels are connected to motor shaft.
(2) Mobile robot moves on a plane surface (on lab-specified floor area).

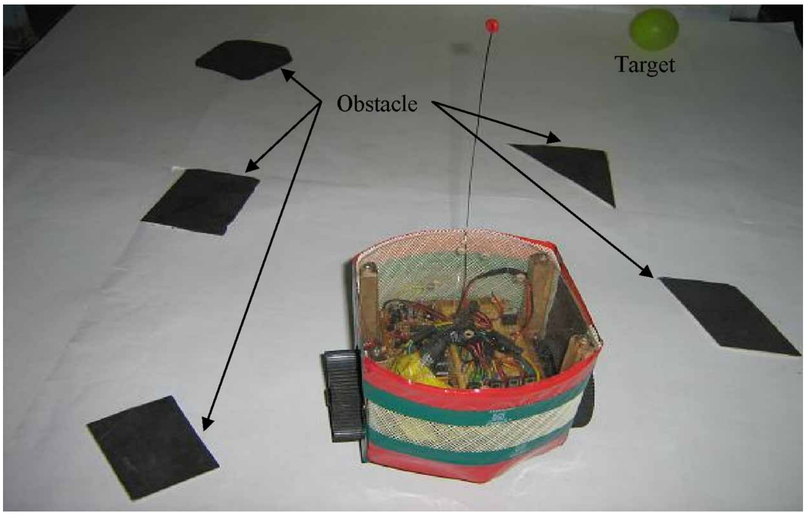

Fig. 14 Real mobile robot at initial position

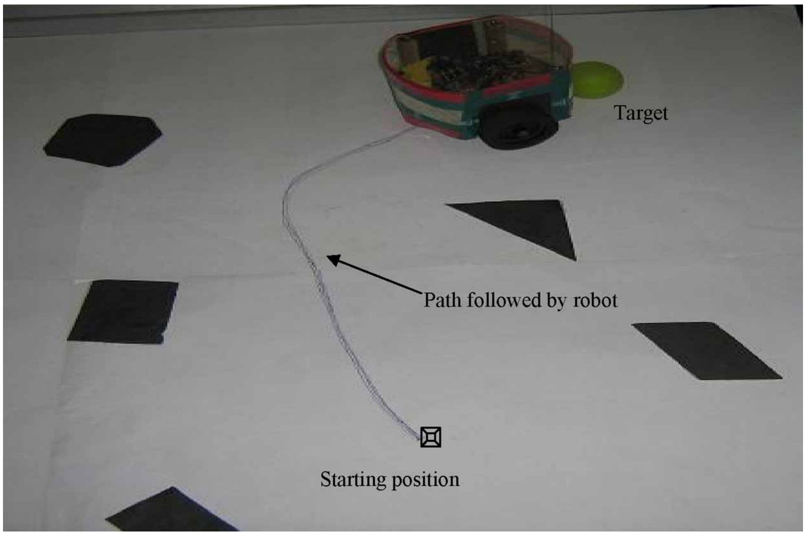

Fig. 15 Real mobile robot reaching the goal

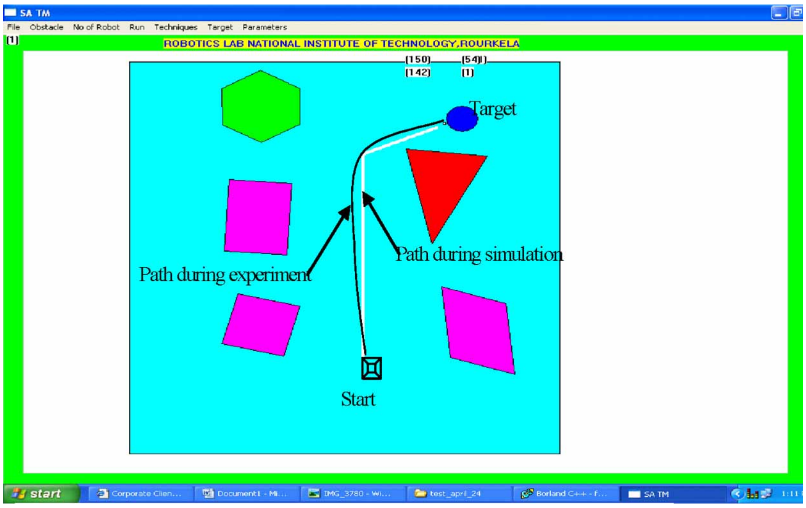

Fig. 16 Path traced by the simulated and actual real mobile robot

Table 5 Time taken by robots in simulation and experiment to reach targets

S. No.	Average of 12 experiments in each environment	Time during simulation (s)	Time during experiment (s)
1	For 1st environmental scenario	28.3	30.5
2	For 2nd environmental scenario	28.4	30.5
3	For 1rd environmental scenario	28.3	30.5

(3) The wheel of a mobile robot rolls on the floor without any translational slip.
(4) The wheel of a mobile robot makes rotational slip at the contact point between each wheel and the floor.

The experimental paths followed by mobile robots to reach the target are obtained as shown in Fig. 15. From the fuzzy controller (inputs: left, front, right obstacle distances, and heading angle) after defuzzification, robots get the left and right wheel velocities, which subsequently give the new steering angles. The paths traced by the robots are marked on the floor by a pen (fixed to the front of the robots) as they move (Fig. 15). The experimentally obtained paths follow closely those traced by the robots during simulation (shown in Fig. 16). From these figures, it can be seen that the robots can indeed avoid obstacles and reach the targets. Table 5 shows the times taken by the robots in simulations and in the experimental tests to find the targets. The figures given are the averages of 12 experiments on each environmental scenario being conducted in the laboratory. To exhibit the superiority of the proposed intelligent controller of mobile robot, the experimental results are verified with simulation modes, which demonstrate the feasibility of this approach.

5 CONCLUSIONS

From the above analytical and experimental analyses, the conclusions drawn are outlined.

1. With the help of the developed fuzzy inference technique, the robots can recognize successfully and reach the target successfully. This has been demonstrated in simulation and experimental results.
2. Various navigational control strategies (e.g. obstacle avoidance, wall-following action, and target seeking) have been addressed in the current developed controller. These behaviours are shown in different simulation and experimental scenarios.
3. A software platform has been developed to verify the results in simulation mode.
4. The experimental results obtained during the navigation of real mobile robots are compared with the simulation results. A good agreement has been seen during comparison.
5. The fuzzy inference technique can be used for path planning of mobile robots in complex hazardous environments.
6. Hybrid techniques may be developed for further investigation in optimizing the navigation paths of robots.

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