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Mobile robot wall-following control using a behavior-based fuzzy controller in unknown environments

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Abstract

This paper addresses a behavior-based fuzzy controller (BFC) for mobile robot wall-following control. The wall-following task is usually used to explore an unknown environment. The proposed BFC consists of three sub-fuzzy controllers, including Straight-based Fuzzy Controller (SFC), Left-based Fuzzy Controller (LFC), and Right-based Fuzzy Controller (RFC). The proposed wall-following controller has three characteristics: the mobile robot keeps a distance from the wall, the mobile robot has a high moving velocity, and the mobile robot has a good robustness ability of disturbance. The proposed BFC will be used to control the real mobile robot. The Pioneer 3-DX mobile robot has sonar sensors in front and sides, and it is used in this study. The inputs of BFC are sonar sensors data and the outputs of BFC are robots left/right wheel speed. Experimental results show that the proposed BFC successfully performs the mobile robot wall-following task in a real unknown environment.

Keywords: Mobile robot, fuzzy control, wall-following control, sonar sensor.

1 Introduction

The autonomous mobile robot is, ideally, to move or work without human operator in the real world, but the unknown, uncertain, and dynamic environments make this task difficult to accomplish. The wall-following task is usually used when the mobile robot is exploring an unknown environment. Related study has shown the reasons for autonomous mobile robots following walls or contours of an object [11]. These depend on the type of mobile robot and its applications. The perspective information is very important in unstructured environments. When facing unfamiliar or unstructured environment (especially outdoors), autonomous mobile robots rely on the perspective information to re-plan the walking paths. Fuzzy theory [14] is based on fuzzy set. The basic spirit accepts the existential fact of the fuzziness phenomenon. The goal is to handle the things concept of fuzzy and uncertain. Fuzzy theory expresses knowledge in the form of linguistic rules to possibly implements expert human knowledge and experience. Therefore, fuzzy theory has widely been applied in various fields, such as automatic train operation system [13], image recognition [12], weather forecast [9], etc. Recently, several researchers [1, 2, 3, 4, 5, 8, 10] have successfully performed mobile robot control by fuzzy controllers. Thongchai et al. [10] described a sonar-based HelpMate robot using fuzzy control. The proposed fuzzy controller combines different information from all sonar sensors as a sensor mechanism. The sonar sensors detect obstacles for HelpMate robot. Al-Sahib and Ahmed [1] proposed a fuzzy logic controller by means of fuzzy decision making method. The controller detects obstacles and leads on the mobile robot from the origin to the destination. A noble fuzzy logic based navigation algorithm was presented to effectively model correct environment and efficiently collect the noisy and uncertain sensory data with low-cost hardware equipment [4]. The fuzzy system with a hierarchical control strategy [2] was used to guarantee robot safety and task accomplishment. In order to incorporate fuzzy logic control with priority-based behavior control, Bao et al. [3] presented a behavior-based architecture using fuzzy logic for

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mobile robot navigation in unknown environments. Based on a sonar ring to realize the navigation in an unknown and complex environment, Qian and Song [8] proposed an algorithm to solve the local trap problems in traditional mobile robot navigation strategy. Farooq et al. [5] reports a fuzzy logic based intelligent controller for a differentially steered mobile robot on wall-following behavior. Three ultrasonic sensors mounted on left side of robot measure the distance from the wall and its orientation with respect to the wall for a mobile robot. All the above-mentioned methods ignore the crucial issue regarding the distance and angle between mobile robot and obstacle. When a mobile robot explores an unknown environment, it will easily fall into a dead end. In order to escape the dead end, the mobile robot needs to rely on other mechanisms. Therefore, the wall-following behavior is more suitable to explore in an unknown environment.

In this study, an efficient behavior-based fuzzy controller (BFC) is proposed to implement mobile robot wall-following control. The inputs and outputs of the proposed BFC are sonar sensors and left/right wheels speed of mobile robot. The BFC consists of three sub-fuzzy controllers, called straight-behavior fuzzy controller (SFC), left-behavior of fuzzy controller (LFC), and right-behavior fuzzy controller (RFC), respectively. Each sub-fuzzy controller represents a different behavior. The BFC has the mode decision making to switch behavior in different situations. Our experiments are divided into two parts. The first part is to test the detour ability of mobile robot in three different environments, whereas the other part is to test the robustness ability of mobile robot when disturbance encounters. Simulation results show that the BFC succeeds in wall-following and is disturbance-free. Final, the proposed BFC was implemented to control a real mobile robot. Experimental results also show that the proposed BFC successfully performs mobile robot wall-following task in a real unknown environment.

This paper is organized as follows. Section II introduces the mobile robot. The proposed behavior-based fuzzy controller is presented in Section III. Section IV describes the simulations results of mobile robot control without/with disturbance. The performance of the proposed controller for mobile robot wall-following control in various environments is evaluated and the values of sonar sensors are analyzed in each time step. Section V describes the results of the mobile robot wall-following control in the real environment. Finally, Section VI summarizes the conclusions.

2 Robot description

In this study, Pioneer 3-DX is adopted to perform wall-following control. The size of mobile robot Pioneer 3-DX is $45 \times 38 \times 25$ cm and shows in Figure. 1. The Pioneer 3-DX mobile robot consists of three wheels, where two wheels are used to drive the mobile robot and one auxiliary wheel is used to keep the stabilization of a mobile robot. Pioneer 3-DX is an Advanced Robotics Control and Operations (ARCOS)-based mobile robot and supports eight sonar sensors for object detection, collision avoidance, features recognition, localization, and navigation. In Figure 2, the positions of sonar arrays in Pioneer 3-DX robot are fixed: one on each side and six facing outward at 20-degree intervals. Sensitivity ranges from 10 centimeters (six inches) to five meters. It has a Hitachi H8S-based microcontroller with advanced embedded ActivMedia Robotics Operating System (AROS) software based on a 32-bit and 44.2368 MHz Renesas SH2-7144 RISC microprocessor. In normal mode, the robot's controller boots into its embedded ARCOS firmware which allows external software running on an onboard or user-supplied computer to control the robot's velocity, acceleration, and other operating parameters, and to receive the estimated position and other data from the robot. These sensors take turns starting to measure distance once every 40 milliseconds. The Advanced Robotics Interface for Applications (ARIA) platform is used for programming. The ARIA platform includes many libraries and packages of C++ function. Wireless TCP/IP Ethernet in the platform connects mobile robot and personal computer (PC).

3 The proposed behavior-based fuzzy controller

In this session, an efficient behavior-based fuzzy controller (BFC) is proposed for wall-following control, and the diagram is shown in Figure. 3. The proposed BFC consists of three sub-fuzzy controllers, called Straight-based Fuzzy Controller (SFC), Left-based Fuzzy Controller (LFC), and Right-based Fuzzy Controller (RFC), respectively. Each sub-fuzzy controller represents a behavior of mobile robot, and the switch is used to change mobile robot behavior. The SFC represents a behavior along the wall. When the mobile robot moves in a straight line, the SFC sub-controller will keep the fixed distance between robot and wall in order to avoid collision or departure the wall. The LFC and RFC represent the behaviors of left turn and right turn. When the mobile robot moves left turn or right turn, the LFC or RFC sub-controller will also keep the fixed distance between robot and wall. The SFC and LFC sub-controllers are two inputs and two outputs, whereas the RFC sub-controller is single input and two outputs. Input and output of each sub-controller are the value of sonar sensor and the vector speed of wheels. The distances S1, S2, S3, and S4 are measured by the referred sonar sensors 3, 2, 1, and 0, respectively. Because the arrangement of eight sonar sensors is symmetric, only four sonar sensors of right side on the robot need to be considered, and vice versa for the other four sonar sensors of left side, referred to sonar sensors 4, 5, 6, and 7 on the robot. In general, a fuzzy controller consists of four parts: fuzzification, rule base, fuzzy inference engine, and defuzzification. The flowchart of a general fuzzy controller is shown in Figure. 4 and described as follows:

a. Fuzzification

Fuzzification is defined as the mapping from a crisp value to a fuzzy set. This step converts real value into degree of linguistic variable. Most fuzzy logic controllers usually use triangular membership functions and trapezoid membership functions.

b. Fuzzy Inference Engine and Rule Base

In this step, the rule base (i.e., IF∼Then∼) is used to inference input linguistic variables to output membership functions. The rule base is composed of expert experience and engineering knowledge. A fuzzy rule is defined as follows.

$$R_i: \text{ IF } x_1 \text{ is } A_1,\ x_2 \text{ is } A_2,\ \cdots,\ x_j \text{ is } A_j,\ \cdots,\ \text{and } x_n \text{ is } A_n,\ \text{THEN } y \text{ is } b_i \tag{1}$$

where $x_1, x_2, \cdots, x_n$ represent the input variables and n denotes the number of inputs. In this study, the minimum operator is adopted to perform AND operator.

c. Defuzzification

The final output of a fuzzy controller converts fuzzy conclusion into a crisp value. In this study, we adopt Center of Area (COA) method to perform defuzification. The COA method is defined as follows:

$$y = \frac{\sum_{i=1}^{R}(\Pi_{j=1}^{n}\mu_A(x_j) \times y_i)}{\sum_{i=1}^{R}\Pi_{j=1}^{n}\mu_A(x_j)} \tag{2}$$

where y represents the output of a controller, $\mu_A(x_j)$ is membership function of fuzzy set A for the input variables x_j, R represents the rule number, and y_i is the output value of consequent part of ith fuzzy rule.

3.1 Straight-based fuzzy controller (SFC)

When the mobile robot is in the wall-following process, the important thing is to maintain the fixed distance between the mobile robot and the wall. The behavior of the proposed straight-based fuzzy controller (SFC) depends on the measurement values of sensors 1 and 0 (i.e., S_3 and S_4). And this behavior of mobile robot is shown in Figure. 5. The proposed SFC obtains the distance and angle information from sensors 1 and 0. When the value of sensor 1 decreases gradually, this means that the mobile robot moves toward the side of wall. In this case, the mobile robot needs to be moved far from the wall. On the contrary, when the value of sensor 3 increases gradually, the mobile robot needs to be moved toward the wall. The three membership functions (i.e., Near, Normal, and Far) of S_3 and S_4 are defined in Figure. 6. The five fuzzy rules of the proposed SFC are shown in Table 1.

INPUTS (AND)		OUTPUTS	
S_4 (cm)	S_3 (cm)	L-Wheel (cm/s)	R-Wheel (cm/s)
Any	Near	20	30
Any	Far	30	20
Near	Normal	25	30
Normal	Normal	30	30
Far	Normal	30	25

Table 1: The Five Fuzzy Rules of the Straight-based Fuzzy Controller.

3.2 Left-based fuzzy controller (LFC)

The left turn behavior of left-based fuzzy controller (LFC) depends on the angle of corner formed by two walls. If the value of S_1 is smaller than the value of S_3, the angle of corner is less than 90 degrees. On the contrary, if the value of S_1 is larger than the value of S_3, the angle of corner is more than 90 degrees. When the angle is less than 90 degrees, mobile robot needs left turn early in order to avoid falling into a dead zone. Oppositely, when the angle of corner is more than 90 degrees, mobile robot keeps the fixed distance moving along the walls and needs left turn lately. Figure. 7 shows the angle of corner based on the values of S_1 and S_3. The three different linguistic variables are used in LFC, such as Close, Normal, and Far. The membership functions of inputs S_1 and S_3 are shown in Figure. 8. Table 2 shows the five fuzzy rules in LFC.

INPUTS (AND)		OUTPUTS	
S_1 (cm)	S_3 (cm)	L-Wheel (cm/s)	R-Wheel (cm/s)
Close	Any	-30	30
Normal	Close	-30	30
Normal	Normal	-15	30
Normal	Far	0	30
Far	Any	0	30

Table 2: The Five Fuzzy Rules of the Left-based Fuzzy Controller.

3.3 Right-based fuzzy controller (RFC)

The right turn behavior of right-based fuzzy controller (RFC) depends on the distance (S_4) between the mobile robot and the wall. If the value of the distance (S_4) is far, the mobile robot needs left turn early to avoid far from the wall in right turn process. Oppositely, if the value of the distance (S_4) is near, the mobile robot keeps a fixed distance from the wall after right turn. This phenomenon is shown in Figure. 9. The two membership functions (i.e., Near and Far) in RFC are shown in Figure. 10. Table 3 shows the two fuzzy rules of RFC.

INPUTS (AND)	OUTPUTS	
S_4 (cm)	L-Wheel (cm/s)	R-Wheel (cm/s)
Near	30	20
Far	30	0

Table 3: The Two Fuzzy Rules of the Right-based Fuzzy Controller.

4 Experimental results

This section evaluates the performance of the proposed behavior-based fuzzy controller for mobile robot wall-following control in various environments and analyzes the values of sonar sensors in each time step. In this study, the time step of the mobile robot is set to 500ms. There are three simulation environments in this experiment. The size of first simulation environment is set as 6 × 5 meters, and the size of second and third simulation environments is set as 10 × 8 meters. The simulation experiment is divided into two parts. First, in example 1 we analyze the movement path of mobile robot when various obstacles encounter in three different environments. Second, in order to evaluate the robustness of the BFC, we add a disturbance into mobile robot in example 2.

Example 1: Mobile Robot Control without Disturbance

Figure 11 shows the trajectory of a mobile robot, the value of sonar sensor 4 (S_4), and the vector speeds of left and right wheels in various environments. Figure 11(a) shows the path of mobile robot wall-following control in environment 1 successfully. In this figure, we can find that the BFC switches to LFC mode when the mobile robot locates in positions A, B and C. In addition, the BFC switches to RFC mode when the mobile robot locates in position D. Figure 11(b) shows the value of sonar sensor 4 and the vector speeds of left/right wheels of mobile robot wall-following control. The trajectory of a mobile robot wall-following control in environment 2 is shown in Figure. 11(c). In environment 2 simulation, a mobile robot is difficult to implement the wall-following control at the positions of A, B, C and D. The simulation results show that the mobile robot using the proposed controller still successfully avoids obstacles and performs the wall-following control. When the sonar sensor 4 cannot detect the wall momently, mobile robot needs to turn right over 90 degrees. Figure 11(d) presents the tremendous change of sensor value at the positions of C and D. Environment 3 (i.e., Figure. 11(e)) is more difficult to control than environments 1 and 2. Figure 11(f) shows that mobile robot successfully performs the wall-following control.

Example 1: Mobile Robot Control with Disturbance

Sometimes the mobile robot suffers the disturbance in the wall-following control, the disturbance rejection capability of the proposed controller is important. The adopted environments in this example are the same with example 1. Figure 12 shows the moving trajectory of a mobile robot, the values of sonar sensors, and the vector speeds of left and right wheels. In order to observe the behavior of mobile robot, we mark the "disturbance" label between two time steps. In this example, the noise with zero mean and a standard deviation (STD) of 0.4 m is regarded as output of the mobile robot. Figures 12(b), 12(d), and 12(f) analyze the three step ranges (i.e., [10, 60] in Figure. 12(a), [310, 360]

Methods / Environments	Proposed method	Farooq et al. [5]	Li et al. [7]
Environment 1	3.292	7.093	5.658
Environment 2	7.528	–	7.531
Environment 3	4.712	15.519	7.173

*Note: – represents that the mobile robot collides with the wall.

Table 4: Comparison Results of Various Methods.

in Figure. 12(c), and [190, 240] in Figure. 12(e)) in various environments, respectively. These figures show that the mobile robot using the proposed controller can quickly restore and keep a fixed distance from the wall when the mobile robot encounters a disturbance. Simulation results show that the proposed controller has the disturbance rejection capabilities when the mobile robot encounters a disturbance.

The performance of the proposed behavior-based fuzzy controller is compared with the Farooqs method [5]. Figure 13 shows the trajectory of a mobile robot using Farooqs method in various environments. In [5], nine fuzzy rules are used for mobile robot wall-following control. In Figures. 13(a) and 13(c), the mobile robot performs wall-following control successfully in environments 1 and 3, but the mobile robot cannot keep a stable fixed distance from the wall. And Figure 13(b) shows that the mobile robot collides with the wall in environment 2.

In order to evaluate the performance of the proposed controller, a root mean square error (RMSE) is adopted in this study. The RMSE is defined as follows:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T_{Total}} (S_4(t) - d_{desired})^2}{T_{Total}}} \tag{3}$$

where T_{Total} denotes the number of total time step, $d_{desired}$ represents the fixed distance between the mobile robot and the wall. Here, $d_{desired}$ is set as 30 cm. If the S_4 is close to $d_{desired}$ in total time steps, this means that the mobile robot can keep a stable fixed distance from the wall.

Recently, several researchers [6, 7] adopted machine leaning technologies for solving wall-following control problems. Hsu and Juang [6] proposed evolutionary wall-following control of a mobile robot using an interval type-2 fuzzy controller (IT2FC) with species-differential-evolution-activated continuous ant colony optimization (SDE-CACO). All fuzzy rules are generated online using a clustering-based approach during the evolutionary learning process. Li et al. [7] proposed a novel recurrent fuzzy cerebellar model articulation controller (RFCMAC) based on an improved dynamic artificial bee colony (IDABC) for performing wall-following control of mobile robot. The proposed IDABC algorithm uses the sharing mechanism and the dynamic identity update to improve the performance of wall-following control. Figure 14 shows the moving trajectory of a mobile robot using IDABC algorithm. These methods [6, 7] need to take a time consuming during the wall-following control training. The training times of wall-following control in [7] is about 54 minutes, whereas the proposed method does not take a training time. Table 4 shows the comparison results of root mean square error using the proposed controller and other methods [5, 7]. Experimental results show that the proposed controller obtains a small RMSE error than other methods [5, 7].

5 Control of a mobile robot in real unknown environment

Because the real environment has the characteristics of uncertainty and unpredictability, the control of a real mobile robot is difficult. This section describes the wall-following control results of the mobile robot in the real environment. In order to evaluate the performance of the proposed BFC, the size of environment is set as 4 × 2 meters (see Figure. 15). Figure 16 shows the wall-following control results of mobile robot in the real environments. Experimental results show that the mobile robot using the BFC successfully performs the wall-following control.

Figure 1: Pioneer 3-DX Mobile Robot.

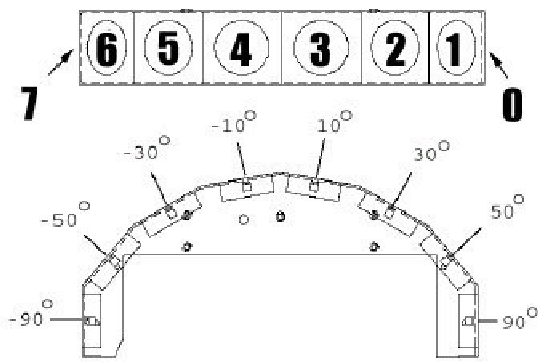

Figure 2: The Arrangement of Sonar Sensors.

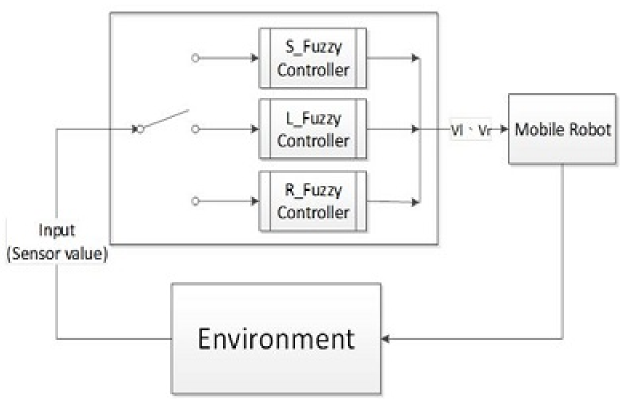

Figure 3: Diagram of the Proposed Behavior-based Fuzzy Controller.

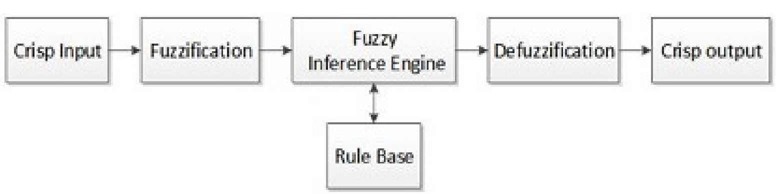

Figure 4: Flowchart of a General Fuzzy Controller.

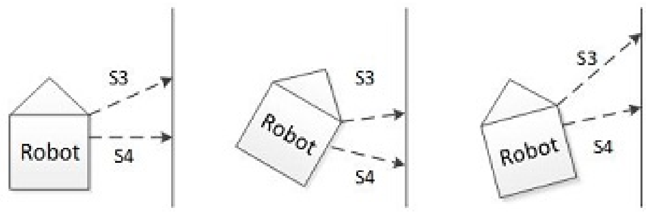

Figure 5: Schematic Diagram of the Straight-based Fuzzy Controller Inputs.

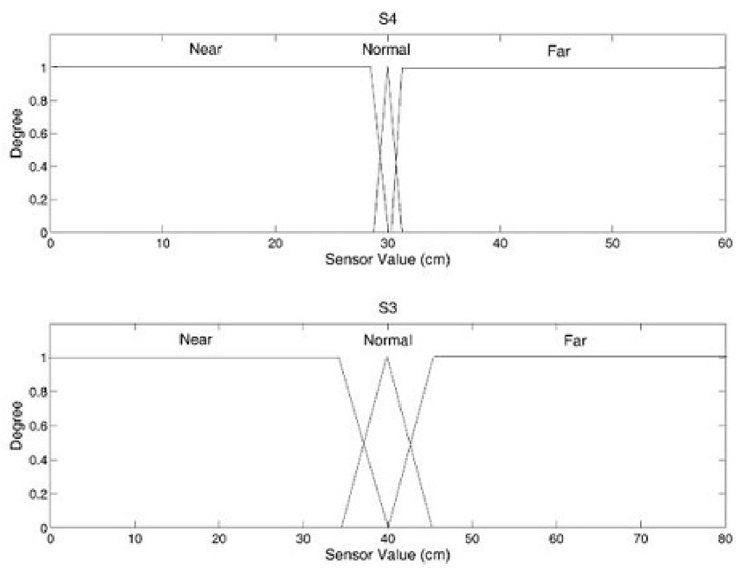

Figure 6: Membership Functions of S4 and S3 in Straight-based Fuzzy Controller.

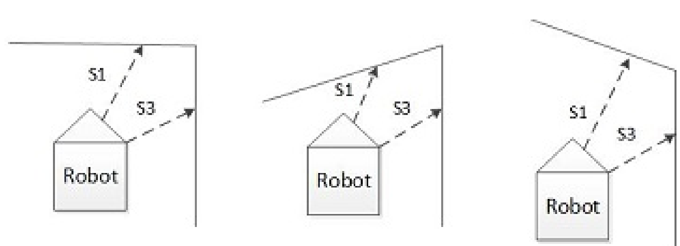

Figure 7: The Angle of Corner Based on the Values of S1 and S3.

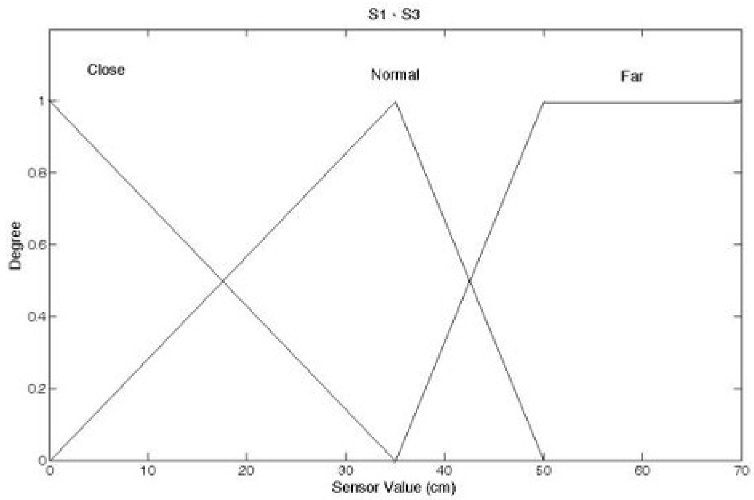

Figure 8: Membership Functions of S1 and S3 in Left-based Fuzzy Controller.

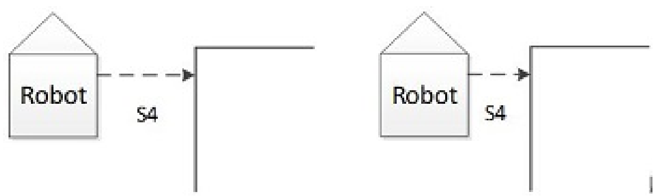

Figure 9: Schematic Diagram of the Right-based Fuzzy Controller Input.

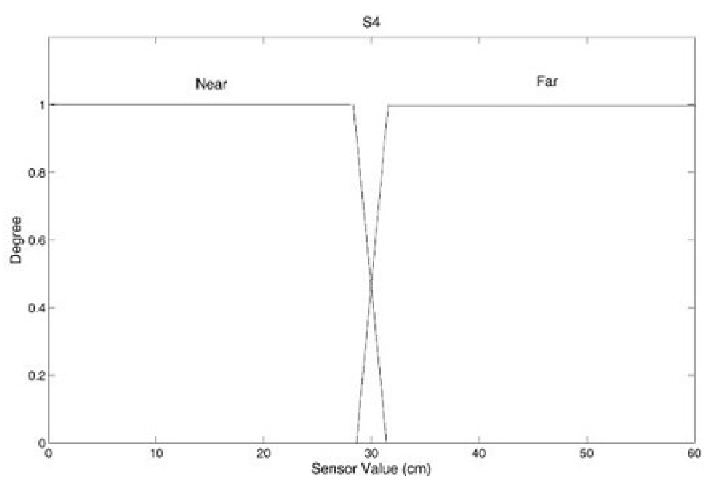

Figure 10: Membership Functions of the Right-based Fuzzy Controller.

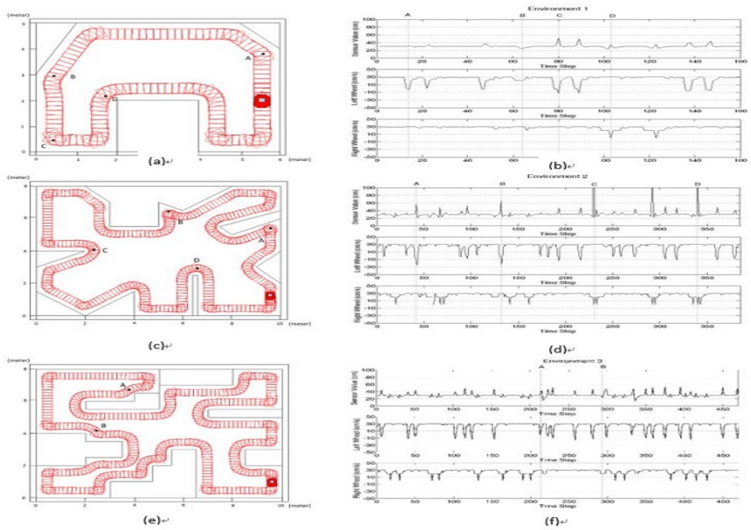

Figure 11: Simulation Results without Disturbance in Three Different Environments. (a), (c),and (e) Represent the Paths of a Mobile Robot; (b), (d), (f) Represent the Value of Sonar Sensors and the Vector Speeds of Left and Right Wheels.

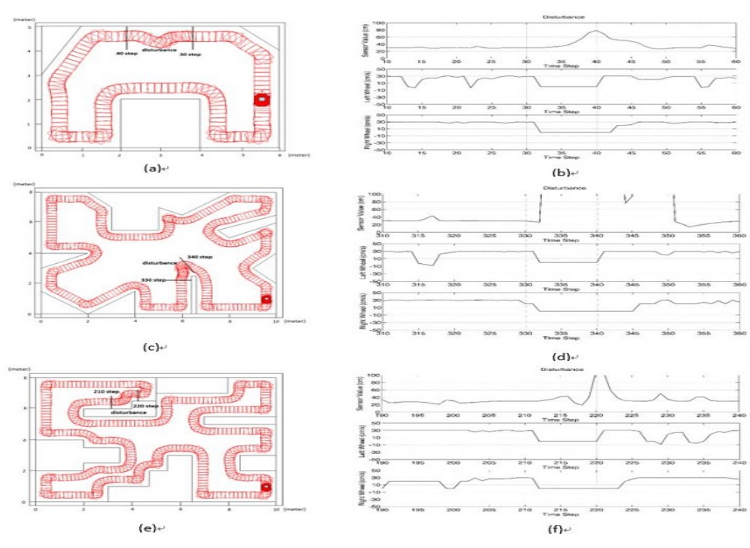

Figure 12: Simulation Results with Disturbance in Three Different Environments. (a), (c), and (e) Represent the Paths of a Mobile Robot; (b), (d), (f) Represent the Value of Sonar Sensors and the Vector Speeds of Left and Right Wheels.

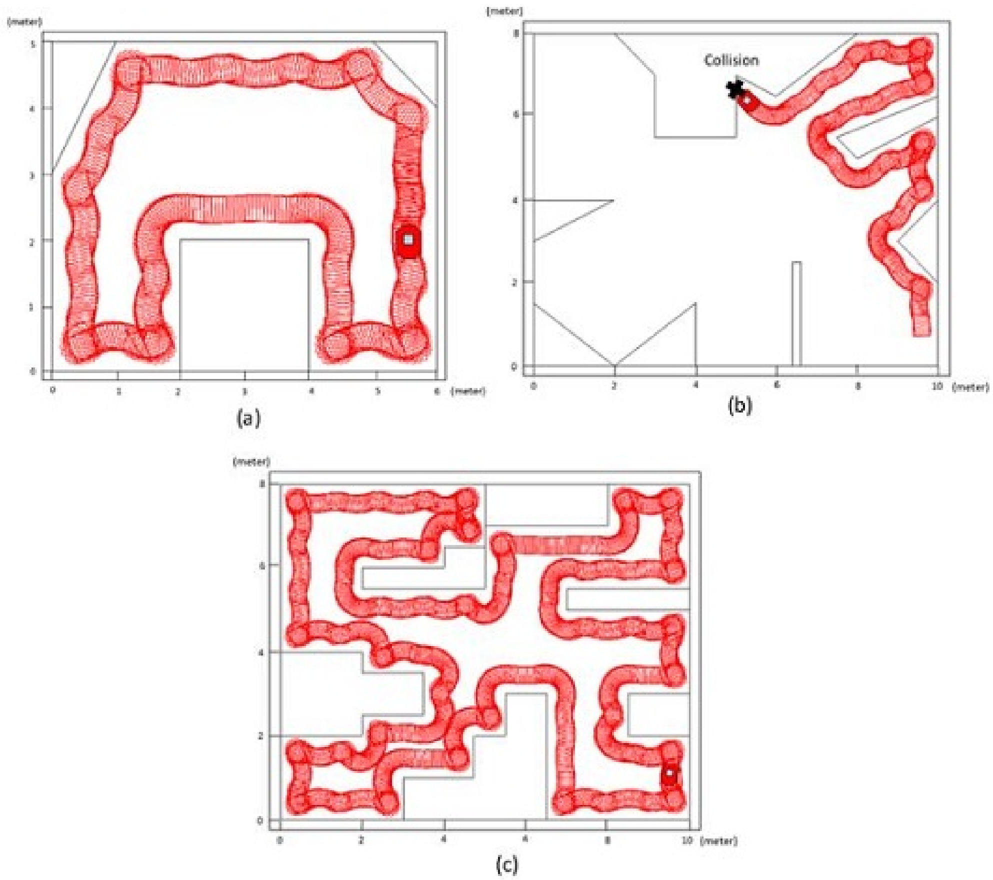

Figure 13: Simulation Results of Farooq et al. [5] in (a) Environment 1, (b) Environment 2, (c) Environment 3.

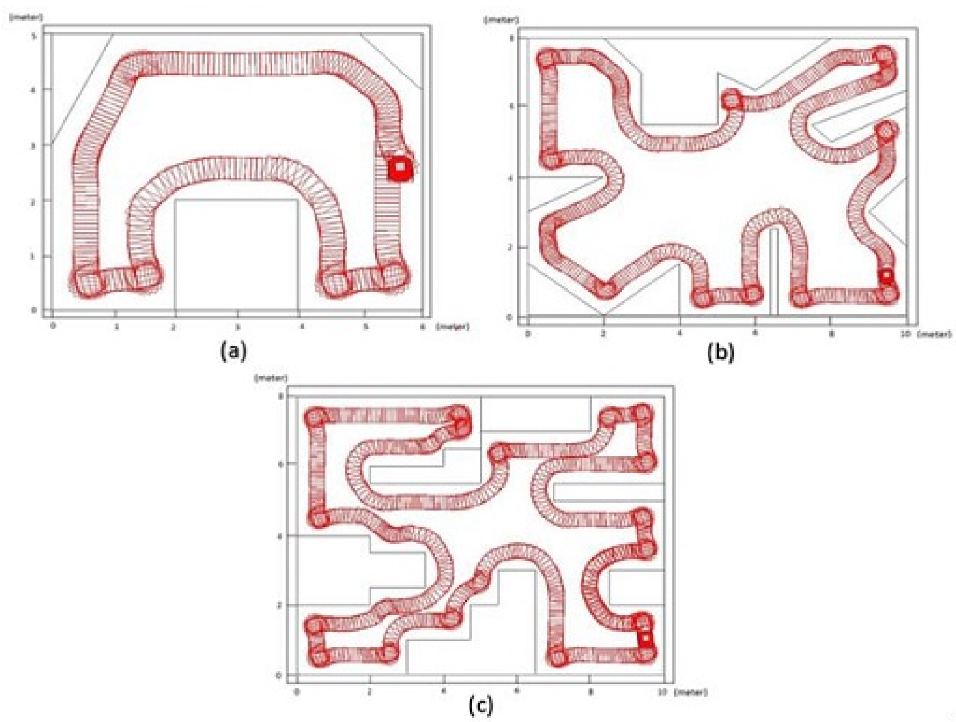

Figure 14: Simulation Results of Li et al. [7] in (a) Environment 1, (b) Environment 2, (c) Environment 3.

Figure 15: The Real Unknown Environment.

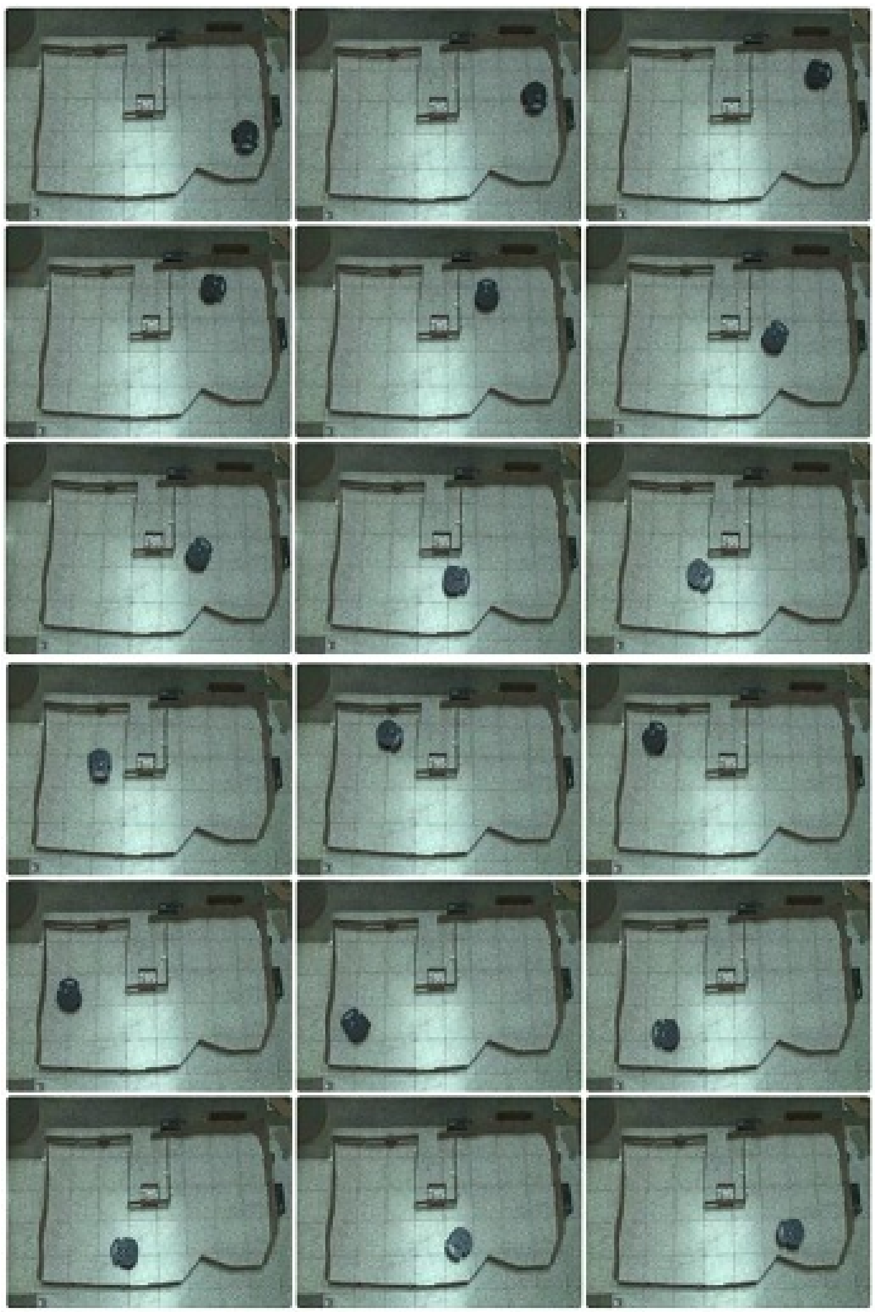

Figure 16: Results of Mobile Robot Wall-following Control in the Real Unknown Environment.

6 Conclusions

In this study, an efficient behavior-based fuzzy controller (BFC) is addressed for the wall-following control of mobile robot. The wall-following task is usually used when the mobile robot is exploring an unknown environment. The proposed BFC is composed of three sub-fuzzy controllers (i.e., SFC, LFC and RFC). Each sub-fuzzy controller represents a different behavior control. The proposed controller can switch to each sub-fuzzy controller according to different behavior situations of mobile robot. The inputs and outputs of the proposed BFC are sonar sensors and vector speeds of left/right wheels. Experimental results show that the mobile robot using the proposed BFC successfully performs the wall-following control. In the proposed BFC, the fuzzy membership functions are still designed by trial and error, this is a time-consuming method. In the future work, we aim to use a reinforcement-based evolutionary computation method for implementing the wall-following and navigation control.

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