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Design of intelligent controller for mobile robot based on fuzzy logic

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Abstract: In order to improve a mobile robot's autonomy in unknown environments, a novel intelligent controller is designed. The proposed controller is based on fuzzy logic with the aim of assisting a multi-sensor equipped mobile robot to safely navigate in an indoor environment. First, the designs of two behaviors for a robot's autonomous navigation are described, including path tracking and obstacle avoidance, which emulate human driving behaviors and reduce the complexity of the robot's navigation problems in unknown environments. Secondly, the two behaviors are combined by using a finite state machine (FSM), which ensures that the robot can safely track a predefined path in an unknown indoor environment. The inputs to this controller are the readings from the sensors. The corresponding output is the desired direction of the robot. Finally, both the simulation and experimental results verify the effectiveness of the proposed method.

Key words: mobile robot; path tracking; obstacle avoidance; fuzzy logic; finite state machine

The mobile robot's self-adaptive navigation in unknown environments is a fundamental and very popular research topic in the field of robotics. In many practical applications, the mobile robot is required to track a predefined path in unknown environments. For example, the robot used for search and rescue which works in some extremely dangerous places has to follow the route set by its operator in order to bypass unavailable regions to approach the destination, and it is usually required to follow the set path as tightly as possible. Meanwhile, the ability to avoid obstacles is also indispensible in a dynamically changing environment.

In recent years, there are various methods involving intelligent navigation for the mobile robot, such as Monte Carlo[1], histogram statistics[2] and fuzzy control[3-4], etc. Generally, the mobile robot is required to work in unknown and unstructured environments concerning which a precise model has not yet been built[5], such as the search and rescue robot (SRR); thus many traditional control approaches fail under such situations. To address these problems, the fuzzy logic is one of the most effective methods due to its capacity of handling uncertain and imprecise information using linguistic rules, and it is widely and effectively used in the field of mobile robots[6-9]. To achieve the purpose of making the robot safely track a predefined path in a dynamically changing environment, we design two basic behaviors based on the fuzzy logic approach to realize respective navigation tasks, and combine them with a finite state machine (FSM) in this paper.

1 Fuzzy Behaviors

The output of the fuzzy logic controller (FLC) for each behavior is expected to change the rotational speed of the robot and its moving direction, and the robot is set to move forward at a constant linear speed. The current location of the robot is obtained by self-dead reckoning based on the encoders of its motors and multi-sensor fusion based on the robot's odometer and inertial measurement units. The robot's direction is provided by its electronic compass. To simplify the problem, we assume that the robot's sensing system works under an ideal state.

1.1 Path tracking behavior

There are various ways to set a path for a robot. In this paper, the path is set by assigning the start point and the end point, and the robot is ordered to follow the straight line connected by these two points.

Fig. 1 shows the robot's local coordination system. The coordinates of the robot's current location, the start point and the end point are defined as $R(x_R, y_R)$, $S(x_S, y_S)$ and $E(x_E, y_E)$. The robot is ordered to track the straight line SE.

The equation of the line SE is

$$ax + by + c = 0 \tag{1}$$

where $a = (y_S - y_E)$, $b = -(x_S - x_E)$, $c = (x_S - x_E)y_S - (y_S - y_E)x_S$.

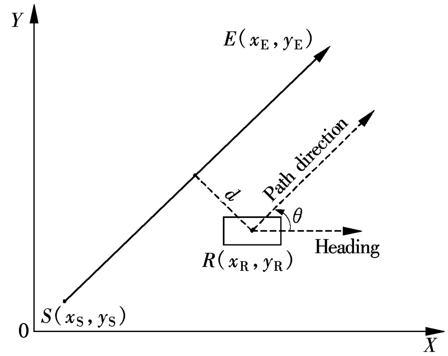

Fig. 1 Local coordination system of the robot

The distance, from which the robot deviates from the line, is defined as d, and it can be calculated as

$$d = \frac{|ax_R + by_R + c|}{\sqrt{a^2 + b^2}} \tag{2}$$

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The d is positive when the robot is above the line, negative otherwise. θ is defined as the angle between the robot's heading and path directions, where $\theta \in (-180°, 180°)$. θ is positive when the robot turns counterclockwise, negative otherwise, and zero when the robot's heading is parallel with the path direction.

The FLC for the path tracking behavior (PTB) is shown in Fig. 2. The inputs to the FLC are d and θ, and the output is the rotational speed of the robot defined as ω. The range of ω is from -50 to 50 (°)/s. ω is positive when the robot turns counterclockwise, negative otherwise. The input and output membership functions are shown in Fig. 3, where NB stands for negative big; NS for negative small; ZE for zero; PS for positive small and PB for positive big. The fuzzy reasoning rules for ω are shown in Tab. 1. Finally, the real output of the FLC can be obtained by the center of gravity method through the defuzzification process. Fig. 4 shows the overall input-output relationship of the path tracking behavior by using Matlab.

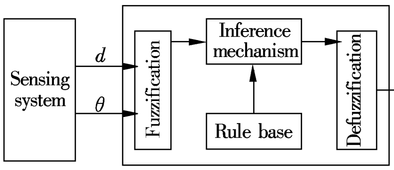

Fig. 2 Fuzzy logic controller for path tracking behavior

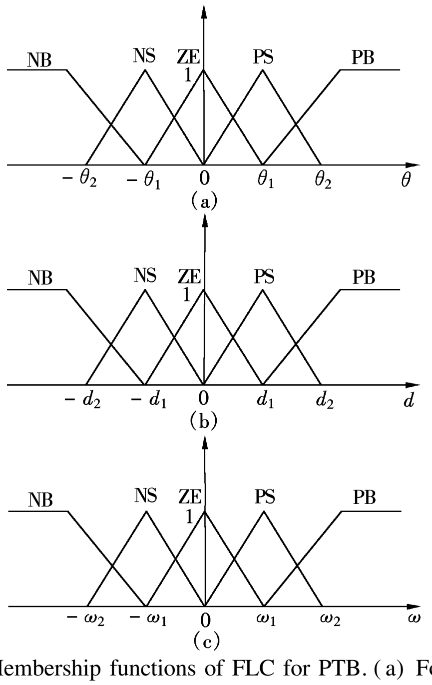

Fig. 3 Membership functions of FLC for PTB. (a) For variable θ; (b) For variable d; (c) For variable ω

Tab. 1 Fuzzy reasoning rules for ω

θ	d				
	NB	NS	ZE	PS	PB
NB	ZE	PS	PB	PB	PB
NS	NS	ZE	PS	PB	PB
ZE	NB	NS	ZE	PS	PB
PS	NB	NB	NS	ZE	PS
PB	NB	NB	NB	NS	ZE

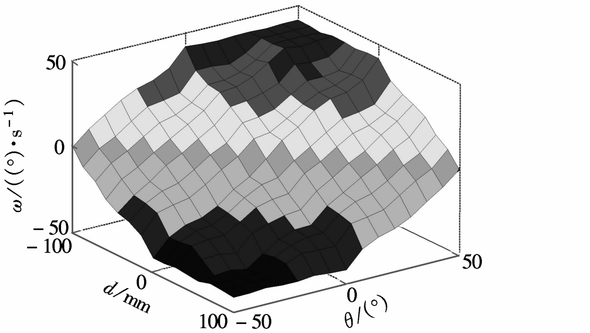

Fig. 4 Input/output relationship of FLC for PTB

1.2 Obstacle avoidance behavior

To guarantee that the robot can safely track a set path in an unknown environment, the obstacle avoidance behavior is indispensible. In view of the fact that the robot is working in the indoor environment and, for simplicity, here we only take into consideration avoiding static obstacles which are in front of the robot to realize the obstacle avoidance behavior (OAB).

The region, which is ahead of the robot with a range of 180°, is divided into two sections along its heading, including the left-front part (LFP) and the right-front part (RFP), as shown in Fig. 5(a). Generally, ultrasonic sensors detect many distance values between the robot and obstacles since there is not only one obstacle in front of the robot in most real environments. Then only the minimum value is taken as the distance (defined as D_o) for consideration of the OAB under such a circumstance. The angle (defined as θ_o, $\theta_o \in (-90°, 90°)$) between the heading of the robot and the edge of the obstacle can be simultaneously obtained by its sensing system, as shown in Fig. 5(b). θ_o is positive when the obstacle is in the LFP of the robot, negative otherwise.

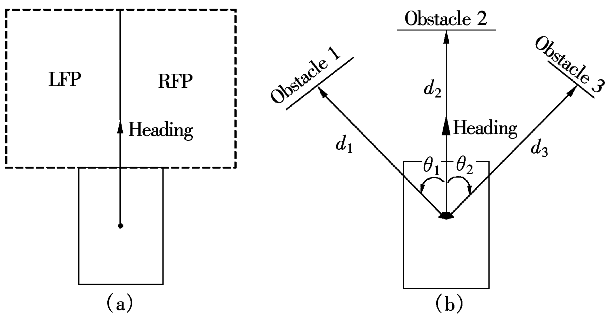

Fig. 5 Sketch of OAB of the robot. (a) Two sections divided in front of the robot; (b) Illustration of positions of obstacles in front of the robot

The input to the FLC for the OAB is D_o, and the output is the absolute value of the rotational speed of the robot, $|\omega|$. We use θ_o to decide the direction of the robot's turning. When $\theta_o = 0$, which means that the obstacle is right ahead of the robot, the angle between the robot's heading and the path direction decides the direction of the robot's rotation. The membership functions of the input and output fuzzy variables are displayed in Fig. 6. We used three fuzzy rules to implement the OAB. They are listed as follows:

1) If the distance from the obstacle is near (N), then the rotational speed is big (B);

2) If the distance from the obstacle is medium (M), then the rotational speed is medium (M);

3) If the distance from the obstacle if far (F), then the rotational speed is small (S).

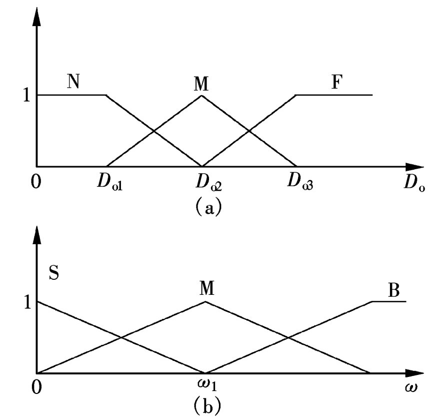

Fig. 6 Membership function of FLC for OAB. (a) For variable D; (b) For variable ω

The overall input-output relationship of the FLC for the OAB is shown in Fig. 7.

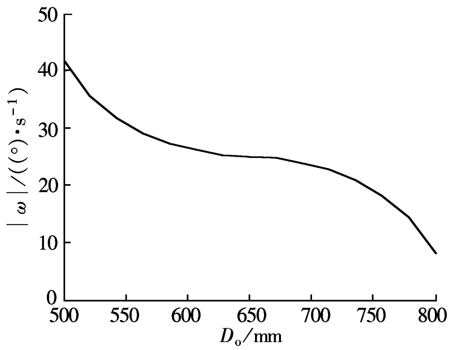

Fig. 7 Input/output relationship of FLC for OAB

2 Behavior Fusion

In order to effectively combine these two behaviors to guarantee that the robot can safely track a predefined path in an unknown indoor environment, a finite state machine (FSM) is proposed, as shown in Fig. 8. It has three states, which are initial-state, path-tracking and obstacle-avoidance, and they are denoted by S_0, S_1 and S_2, respectively. The robot is ready to start performing the task when it is in the state of S_0.

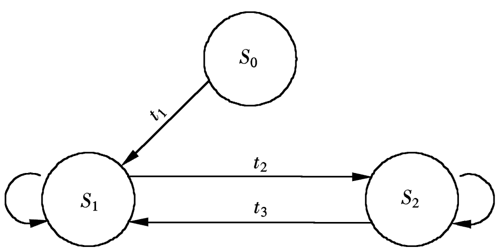

Fig. 8 FSM for behavior fusion

In the state of S_1, the PTB is activated to follow a set path. It can succeed in tracking a pre-appointed straight line in an indoor environment where there is no obstacle. But in the state of S_2, the OAB is activated to avoid obstacles in front of the robot. It can guarantee that the robot can safely drive in an unknown environment.

Initially, the robot is in the state of S_0. The transition t_1 occurs once when the robot receives a command of starting to follow a set path. Then the PTB is activated to make the robot follow the set path in the state of S_1. If the robot encounters obstacles within a certain distance (predefined) while tracking, as displayed in Fig. 5(b), t_2 occurs. Then the state is transferred to S_2. The transition t_3 occurs as the distance between the robot and the obstacle is greater than the predefined value, which means that the robot is "safe" now. Then the state is set back to S_1 to continue the path tracking. Finally, the robot cycles within each state and between them, which realizes the design goal of the FSM.

If the robot is required to reach a certain target after following several predefined paths, we can add a state to the FSM to fulfill this need. This state checks the robot whether it arrives at the terminal of the last set path, which is completed by comparing the coordinates of the robot and the end point of the path.

3 Simulation and Experimental Results

3.1 Simulation

To verify the effectiveness of the proposed method, several simulations are performed based on the Pioneer3 AT simulator. The robot is set to move forward at 200 mm/s both in simulation and real experiments. First, only the PTB is realized. Fig. 9 displays the result trajectory of the robot which tracks a predefined path under the control of the PTB in a no obstacle case. The path is a straight line denoted by two points, S and E. It is marked by dashed lines in Fig. 9 and the following figures, and the actual track of the robot is indicated by real lines. The robot heads along the forward direction of the X-axis at the start position R. Fig. 9 (a) shows the result trajectory of the robot which starts below SE. Fig. 9(c) shows the result in which it starts above SE. Figs. 9(b) and (d) show the curves of d and θ recorded during experiments. When d keeps within ± 15 mm and θ within ± 10°, the robot can be considered to be tracking the predefined path accurately. Calculated from the data of d and θ recorded during these two experiments, the time it takes the robot to successfully track the path from the start position (referred as tracking time below) is 28.9 and 26.4 s, respectively. After that, the robot keeps following the set path accurately, which verifies the effectiveness of the FLC for the PTB. Fig. 10 illustrates the result trajectory of the robot which tracks the same path (denoted as SE) under the control of the FSM designed in section 3 with obstacles and several parameters recorded during the tracking, including d, θ, the robot's heading and its rotational speed ω. In this figure, rectangles represent obstacles. The robot has the same start position and heading direction as those shown in Fig. 9(a). It also successfully tracks the set path after bypassing obstacles encountered during the procedure. The tracking time of the robot in this experiment is 64.2 s.

3.2 Experiment

We directly load the software into Pioneer3 AT robot without any modifications to carry out three real experiments as expressed below. First, it is ordered to follow the

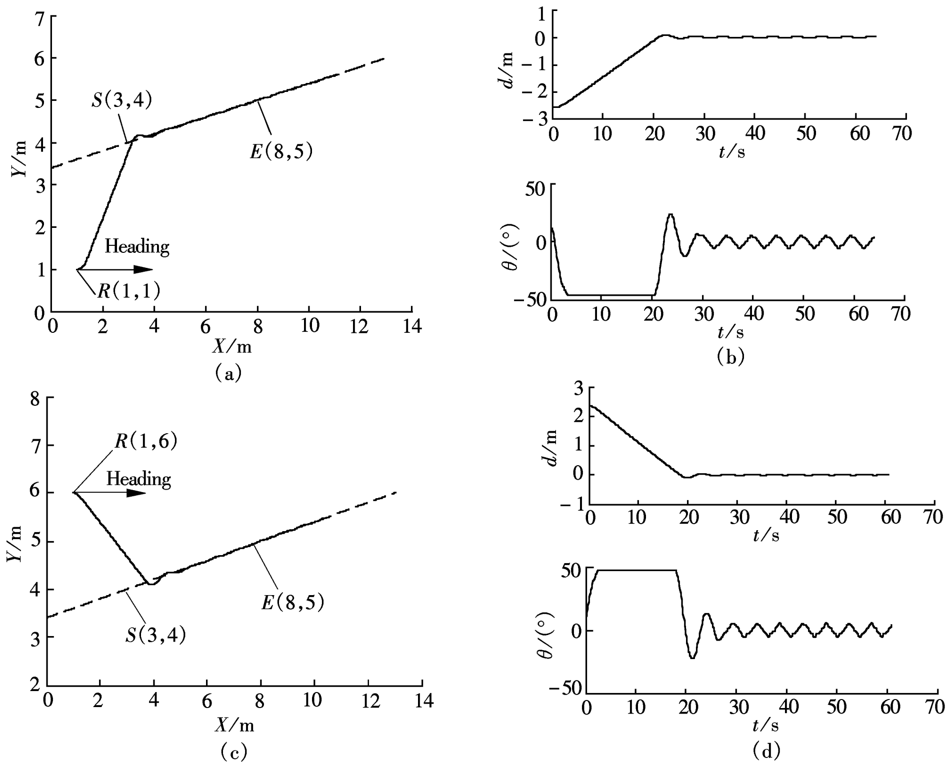

Fig. 9 Simulation results of robot tracking without obstacles. (a) Trajectory of robot started below *SE*; (b) Curves of d and θ of robot starting below *SE* during tracking; (c) Trajectory of robot started above *SE*; (d) Curves of d and θ of robot starting above *SE* during tracking

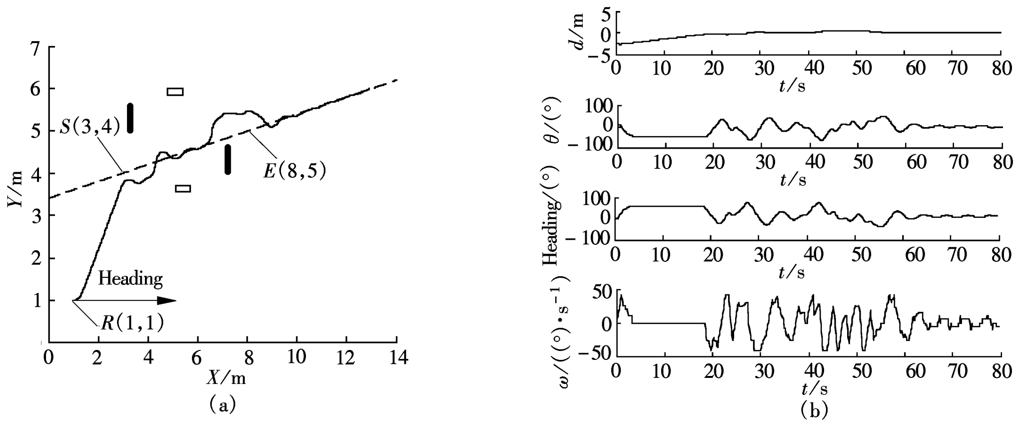

Fig. 10 Simulation results of robot tracking with obstacles. (a) Trajectory of robot with obstacles; (b) Curves of parameters of robot during tracking

same path (denoted as *SE*) set in the simulation in a lab environment without obstacles from positions below and above the path. The robot starts at the same positions with those shown in Figs. 9(a) and (b), and also heads along the forward direction of the *X*-axis. Fig. 11 shows the result trajectory of the robot and the curves of d and θ recorded during tracking. Fig. 11(a) shows the result trajectory of the robot which starts below *SE*. Fig. 11(c) shows the result in which it starts above *SE*. Figs. 11(b) and (d) show the curves of d and θ recorded during the respective experiments. The tracking time of the robot in these two experiments is 24.1 and 22.3 s, respectively. Then the robot is made to track *SE* in the same environment but with obstacles arranged similarly to those shown in Fig. 10(a). Fig. 12 illustrates the result trajectory of the robot and curves of the same parameters with those shown in Fig. 10(b) which can provide a strong verification of the effectiveness of the proposed method. The robot has the same start position and direction as those shown in Fig. 10(a). As can be seen from Fig. 12, the robot finally tracks the predefined path accurately though there are some obstacles in its way. The tracking time in this experiment is 55.5 s.

The tracking time in three experiments of simulation and real experiment is listed in Tab. 2. Considering the errors of measurements, the results of simulations and real experiments are consistent with each other and verify the effectiveness of the proposed method.

Tab. 2 Tracking time of simulation and experiment s

Type	First experiment	Second experiment	Third experiment
Simulation	28.9	26.4	64.1
Real experiment	24.1	22.3	55.5

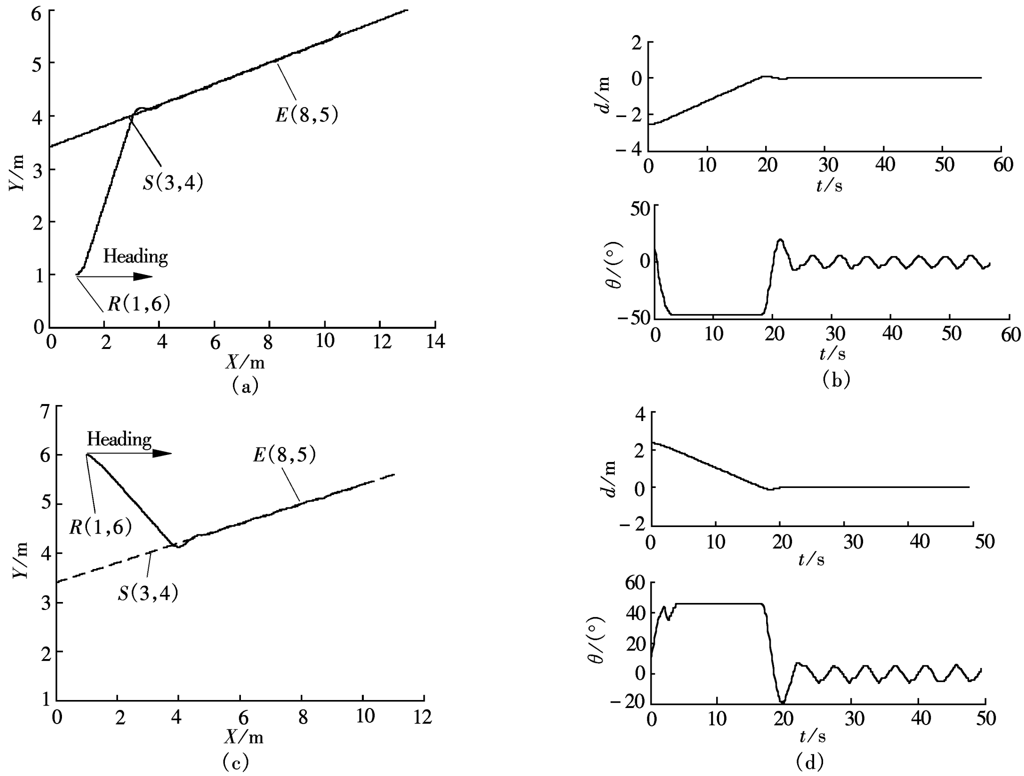

Fig. 11 Experimental results of robot tracking without obstacles. (a) Trajectory of robot started below *SE*; (b) Curves of *d* and *θ* of robot starting below *SE* during tracking; (c) Trajectory of robot started above *SE*; (d) Curves of *d* and *θ* of robot starting above *SE* during tracking

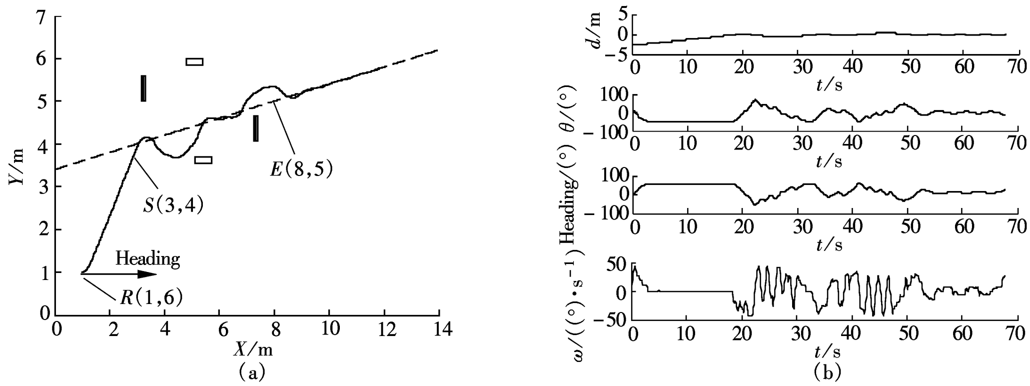

Fig. 12 Experimental results of robot tracking with obstacles. (a) Trajectory of robot with obstacles; (b) Curves of parameters of robot during tracking

4 Conclusion

Tracking a set path and avoiding surrounding obstacles during the movement are quite valuable in many applications of a mobile robot. Based on the fuzzy logic control approach, this paper develops two controllers to realize primitive behaviors of the robot, including path tracking behavior and obstacle avoidance behavior. These two behaviors are combined with the FSM; therefore, the robot can safely track a predefined path in a dynamically changing indoor environment. This method is simple, yet effective and robust, as demonstrated by both the simulation and experimental results, and it is suitable for most mobile robots. In the future, vision will be taken into account to extend the function and improve the adaptability of the system. We will continue to investigate the behavior method for more complex tasks.

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基于模糊逻辑的移动机器人智能控制器设计

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摘要: 为了提高移动机器人在未知环境下的自主性, 设计了一种基于模糊逻辑的智能控制器. 该控制器可以辅助装备多传感器的机器人在室内未知环境下安全地进行自主导航. 首先, 基于模糊逻辑设计了 2 种实现移动机器人智能导航的行为: 路径追踪行为和避障行为. 使用模糊逻辑的方法可以通过模仿人类驾驶经验, 降低移动机器人在未知环境下实现自主导航的复杂性. 然后, 利用有限状态机对 2 种行为进行融合, 以确保在未知的室内环境下机器人能够安全地追踪一条事先指定的路径. 控制器的输入为机器人的传感器数据, 输出为要求机器人运动的方向. 最后, 仿真和实验结果证实了该控制器的有效性.

关键词: 移动机器人; 路径追踪; 避障; 模糊逻辑; 有限状态机
中图分类号: TP242