Design and Implementation of Vision-Based Fuzzy Obstacle Avoidance Method on Humanoid Robot

Ching-Chang Wong, Chih-Lyang Hwang, Kai-Hsiang Huang, Yue-Yang Hu, and Chi-Tai Cheng

Abstract

A vision-based fuzzy obstacle avoidance method is designed and implemented on a humanoid robot so that it can avoid obstacles successfully and arrive at the terminal area effectively. A humanoid robot with 23 degrees of freedom is implemented so that it can execute six basic walking motions. One vision system and one electronic compass are installed on the robot to obtain the environment information so that it can obtain the environment information to be an autonomous mobile robot. In order to avoid obstacle successfully, the minimal distance between the robot and the obstacles in the moving direction measured from the captured image of the vision system is considered as a dangerous factor in the moving direction. In order to attend at the terminal area effectively, the angle difference between the goal direction and the moving direction of the robot measured from the electronic compass is considered as a helpful factor in the moving direction. The dangerous factor and the helpful factor are considered to be two inputs of the proposed fuzzy system to evaluate the feasibility of each motion so that one of the six motions with a highest value is selected to be the next motion in every decision. Some simulation results in four different environments by placing different number of obstacles and one practical experiment of a difficult environment are presented to illustrate the effectiveness of the proposed method.

Keywords: Humanoid robot, Autonomous mobile robot, Vision-based robot, Obstacle avoidance, Fuzzy system.

1. Introduction

Fuzzy theory has been used in many kinds of robot design. For mobile robots, the fuzzy logic approach was a good and effective solution to the topic of obstacle avoidance [1-3]. In [4], a fuzzy logic controller for mobile robots was designed and implemented on the small-sized robot soccer system. The planner level generated a path to the destination by avoiding obstacles. The motion control level calculated the robot's wheel velocity so as to follow the path generated by the planner as to the current robot posture. In [5], a robot behavior decision-making subsystem with a fuzzy control strategy was designed and implemented on a mobile robot with the stereo vision subsystem. The fuzzy control strategy can make the mobile robot target tracking and obstacle avoidance precisely. Except for the wheeled mobile robot, in [6], a fuzzy algorithm was proposed to control the humanoid robots. A balancing control algorithm based on a fuzzy controller using 3D images was designed and implemented on the biped robot. The fuzzy controller based on the obtained pose and velocity of the robot can let the biped robot keep in a stable pose. In [7], according to the sensor information obtained from a 3-axis accelerometer, a fuzzy balancing control method with two two-input-and-one-output fuzzy systems was designed and implemented on a small-sized humanoid robot so that it can stand and balance on an inclined plane. In addition to generally common robots, in [8], a fuzzy control based intelligence was designed and implemented on a robot fish so that it can swim autonomously and be controlled through a remote control. The intuitive control and the fuzzy control were used to avoid obstacle and track targets.

Obstacle avoidance is one of important topics in the humanoid robot design. For the robot soccer games such as RoboCup, the humanoid robot must have the ability to avoid the other robots to search, track, or dribble the ball in the game field. For the humanoid robot competitions such as the HuroCup league in FIRA Cup, the obstacle avoidance is one of eight events in the competition. So the ability to avoid obstacles is an important function for autonomous humanoid robots. Most of the researches on the topic of obstacle avoidance for the humanoid robot are stepping over obstacles [9-11], obstacle avoidance control of humanoid robot ram [12, 13], a humanoid robot passing through a door [14], and a humanoid robot passing under obstacle [15]. There are fewer researches to discuss how to let the humanoid robot walk through an environment with many obstacles (e.g. the blue file with a height of approximately 30 cm is used to be the obstacle). In [16], a fuzzy system based on the obtained
information of four infrared (IR) sensors and one electronic compass was designed and implemented on a small-size humanoid robot to avoid obstacles. But there is no research to discuss a real-time obstacle avoidance method based on the obtained vision information for a humanoid robot to be navigated in an unknown environment. Therefore, in this paper, a humanoid robot with a vision system is implemented and a vision-based fuzzy obstacle avoidance method is proposed to be implemented on this robot to illustrate the effectiveness of the proposed method on the obstacle avoidance problem.

In order to let the behavior of humanoid robot be similar to that of the human, the sensor must be at a position of the humanoid robot roughly equivalent to the location of the human. Moreover, active sensors (emitting light, sound, or electromagnetic waves into the environment in order to measure reflections) are not allowed to be installed in the robot, so only the image sensors can be installed on the humanoid robot. In this paper, a real-time obstacle avoidance problem for a humanoid robot to be navigated in an unknown environment based on the obtained vision information is considered. The humanoid robot must walk across a designated zone and can not collide with obstacles in the field. Therefore, an effective and convenient method must be proposed to measure the distance between the robot and the obstacle. In this paper, the full image frame is divided into five areas and the obstacle in every divided area is detected respectively. According to the height of the obstacle in the divided area, the relative distance between the obstacle and the robot are obtained. That is, the scanning lines of vision are used to replace the detection of active sensors in the implementation. According to the vision information, an obstacle avoidance method based on the fuzzy system concept is proposed and implemented on a small-sized humanoid robot so that it can be navigated in an unknown environment.

The rest of this paper is organized as follows: In Section 2, the system architecture of the implemented humanoid robot and six basic walking motions are described. In Section 3, a distance measurement in the vision system is proposed. One image frame in one direction is divided into five bar areas and each area is considered as a scanning line of vision. Three directions are considered so that fifteen scanning lines of vision are used to measure the distance between the robot and the obstacle. The information of obstacles in every divided area can be transformed into a relative distance between the robot and obstacles. In Section 4, a vision-based obstacle avoidance method based on the fuzzy system concept is proposed to decide an appropriate behavior from six motions in each decision so that the vision-based robot can avoid obstacles and arrive at the terminal area effectively. In Section 5, four simulation results and one practical experiment result are presented to illustrate the effectiveness of the proposed fuzzy obstacle avoidance method. In Section 6, some conclusions are made.

2. System Architecture Design of Humanoid Robot

In this paper, a vision-based autonomous humanoid robot with 23 DOF (degrees of freedom) is design and implemented to realize the proposed obstacle avoidance method. There are four main parts in the system architecture design: (a) mechanism design, (b) electronic system design, (c) vision system design, and (d) gait design. They are briefly described as follows:

In the mechanism design, the DOF configuration and the photograph of the implemented humanoid robot are described in Fig. 1. There are 2 DOF on the neck, 1 DOF on the waist, 8 DOF on two arms, and 12 DOF on two legs for this humanoid robot. Its height and weight are 56 cm and 3.1 kg, respectively.

![Fig. 1. The DOF configuration of the implemented humanoid robot and its photograph.](image-url)

In the electronic system design, the system block diagram of the implemented humanoid robot is described in Fig. 2, where one vision system and one electronic compass are installed on the robot to obtain the environment information so that a fuzzy obstacle avoidance method based on the obtained information can be proposed and implemented on this robot to let it be a vision-based autonomous robot. Two control boards are used to realize the structure. One is a TKU-Board [17] which is a PC-based control board with an Intel Pineview-D510 processor. It is used to process the image information and the proposed fuzzy obstacle avoidance method is built on it to decide strategies. The other is a FPGA development board with an embedded soft-core processor NIOS II. It is used to receive the data obtained by sensors and control the motion of motors. A USB webcam installed on the robot is used to capture its en-
environment image and the TKU-Board is used to obtain the information of environment. The TKU-Board decides an appropriate motion according to the processed image data, and then transmits a motion command to the FPGA development board through RS-232. The NIOS II processor transforms the command into some control signals to drive motors so that the desired behavior of the robot can be executed exactly.

In the vision system design, a USB webcam is installed on a two-dimensional neck mechanism so that the visible area of the robot is expanded by the mechanism to obtain its environment image. The process of the vision system containing image acquisition, image processing, and object recognition is built on the TKU-Board by using Visual Studio 2008 C++.

In the gait design, gaits of the humanoid robot are divided into several parts to accomplish. All motions of the robot are produced from the motion of marking time [18]. The motion of marking time is divided into three sub-motions containing shifting center of gravity, raising leg, and spreading leg. In this paper, six basic motions including “slipping left (m₁)”, “turning left 30° (m₂)”, “walking forward (m₃)”, “turning right 30° (m₄)”, “slipping right (m₅)”, and “walking more forward (m₆)” are designed based on the method. The diagram of the six motions for the movements of the robot is shown in Fig. 3.

![Diagram](image)

**Fig. 3.** Description of six walking motions of the implemented humanoid robot: (a) slipping left (m₁), (b) turning left 30° (m₂), (c) walking forward (m₃), (d) turning right 30° (m₄), (e) slipping right (m₅), and (f) walking more forward (m₆).

### 3. Distance Measurement in Vision System

In this paper, the webcam installed on the implemented humanoid robot is the only sensor that can be used to detect obstacles. In order to provide the required information of obstacles for the proposed obstacle avoidance method, as shown in Fig. 4, the image frame divided into five bar areas is proposed. The height of obstacle in one bar area of the image can be viewed as the distance information of obstacle in one direction of scanning line. If the height of the obstacle is higher, it means that the obstacle is closer to the robot. Five bar areas divided form the image frame are viewed as five scanning lines of vision to measure the distance between the robot and the obstacle. The implemented robot uses the vertical dimensional of the two-dimensional neck mechanism to adjust its visible distance to 45 cm. This distance can let the robot have enough time to execute the motion of avoidance. This also let the robot can not see the other obstacles behind the current obstacle. When the robot is close to the obstacle gradually, the image of obstacle emerges from the top of the image frame gradually. So the height of the obstacle in the image frame can be used to display the relative distance between the robot and the obstacle.

Three situations and image frames of different distances between the robot and the obstacle are shown in Fig. 5. If the distance between the robot and the obstacle is not near enough such as the situations described in Fig. 5(a) and Fig. 5(c), the top edge of the recognized object in the five bar areas of the image frame coincides with the top edge of image frame. So the height of obstacle in one bar area can be viewed as the distance information.
of obstacle in one direction of scanning line such as that described in Fig. 5(b) and Fig. 5(d). Oppositely, if the distance between the robot and the obstacle is near enough such as the situation described in Fig. 5(e), the top edge of the recognized object in the five bar areas of the image frame doesn’t coincide with the top edge of image frame such as that described in Fig. 5(f). Then the bottom edge of the recognized object in the five bar areas of the image frame can be used to represent the relative distance in the situation of near distance such as that described in Fig. 5(e). If the coordinate of the bottom edge for the recognized object in one bar area of the image frame is lower, it means that the obstacle is closer to the robot. The pixels of the image frame are 320×240. Whether the height of obstacle or the coordinate of the bottom edge for the recognized object in one bar area of the image frame, the values represented the relative distance between the obstacle and the robot in the image frame are from 0 to 240. The value 0 indicates that the real distance between the obstacle and the robot is farther than 45 cm. Oppositely, the value 240 indicates that the real distance between the obstacle and the robot is almost zero. So the real measured distance of the vision scanning line can be described by

$$d_{SL} = \frac{(16 \times 45 - 3Y_{Horc})}{16}$$

(1)

where $d_{SL}$ is the real measured distance of every vision scanning line and $Y_{Horc}$ is the height of obstacle or the coordinate of the bottom edge for the recognized object in one bar area.

The visible scope of the webcam installed on the two-dimensional neck mechanism is about 60°. In order to avoid touching any obstacles when the robot executes the motion of slipping, the visible scope of the robot must exceeds 180° because there is a definite thickness for the body of the robot. Thus the two-dimensional neck mechanism is turned three directions to detect obstacles in the consideration of the real-time implementation. One direction is the center of the face, and the others are turning left 75° and turning right 75°. But the line of vision is hampered by the shoulders (see Fig. 6) when the robot turns left 75° or turns right 75° to detect obstacles only by turning the two-dimensional neck mechanism. Therefore, the turning mixed the motion of the two-dimensional neck mechanism with the motion of waist (see Fig. 7) is used to detect obstacles in this implementation. Thus three detecting directions shown in Fig. 8 are used for the implemented robot. In this way, fifteen scanning lines as described by Fig. 9 are considered to obtain the image information, where Left (left), Center (center), and Right (right) are respectively denoted by L (l), C (c), and R (r).
4. Vision-based Fuzzy Obstacle Avoidance Method

As shown in Fig. 10, a system structure of fuzzy obstacle avoidance method is proposed based on the obtained environment information from the scanning lines of vision and the electronic compass. There are six walking motions. First, the fuzzy system is proposed to determine an evaluation value of each motion. Then the motion with a highest evaluation value is selected to be the next motion from six motions to avoid obstacles successfully and arrive at the terminal line effectively. As shown in Fig. 10, $d_i$ and $\phi_i$ are chosen to be the input variables and $f_i$ is chosen to be the output variable of the two-input-and-one-output fuzzy system based on the obtained information from the scanning lines of vision and the electronic compass. They are described as follows:

$$d_{i_1} = \min(d_{L1}, d_{CL})$$

$$d_{i_2} = \min(d_{L2}, d_{CL}, d_{CR}, d_{CCL}, d_{CCL})$$

$$d_{i_3} = \min(d_{L3}, d_{CL}, d_{CR}, d_{CCL})$$

$$d_{i_4} = \min(d_{L4}, d_{CL}, d_{CR}, d_{CCL}, d_{CCR})$$

$$d_{i_5} = \min(d_{L5}, d_{L4}, d_{L5}, d_{L6})$$

$$d_{i_6} = \min(d_{L6}, d_{CL}, d_{CL}, d_{CCL}, d_{CCL}, d_{CCR}, d_{CCR}, d_{CCR})$$

where obstacles in the moving direction of the $i$-th motion is the important environment information for the $i$-th motion so that some appropriate vision scanning lines.
are selected to determine \( d_i \).

Based on the obtained information from the electronic compass, the angle \( \phi_i \) is chosen as the second input variable of the fuzzy system. This input variable is considered as a helpful factor of the motion. If the angle \( \phi_i \) of the \( i \)-th motion is larger, it means that it is more helpful to execute the \( i \)-th motion for the robot to attend at the terminal line effectively. The angle \( \phi_i \) of the \( i \)-th motion can be described by

\[
\phi_i = 180 - \left| \theta_M + \theta \right|, \quad i = 1, 2, \ldots, 6 \tag{8}
\]

and

\[
\theta_M = \theta_R - \theta_G \tag{9}
\]

where \( \theta_G \) is the angle of the goal direction, and \( \theta_R \) is the angle of the body direction of the robot obtained by the electronic compass installed on it, as shown in Fig. 11. \( \theta_M \) is the angle difference between the robot’s direction and the goal direction. The value \( \theta \) is the angle of the moving direction when the new motion is executed. According to the moving direction, the angle \( \theta \) of each motion is described by \((\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6) = (90, 30, 0, -30, -90, 0)\). The angle \((\theta_M + \theta)\) is the relative value of the angle different between the goal direction and the moving direction of the \( i \)-th motion for the robot’s direction in the present. If the value \( |\theta_M + \theta| \) is larger, it means that the angle diverged from the direction of the terminal for the robot is larger.

\[
\begin{align*}
\text{Fig. 11. The relative angle of the goal direction and the direction of the robot.}
\end{align*}
\]

As shown in Fig. 10, a two-input-and-one-output fuzzy system based on the obtained information from the scanning lines of vision and the electronic compass is proposed to evaluate the feasibility of the next motion of the robot. As shown in Fig. 3, there are six walking motions. The evaluation value of the \( i \)-th motion is denoted by \( f_i \) and described by

\[
f_i = f(d_i, \phi_i), \quad i = 1, 2, \ldots, 6 \tag{10}
\]

In the proposed method, \( f_i \) is the output of the fuzzy system. The fuzzy rule base used for the proposed fuzzy system is described in Table 1, where each rule can be described by

\[
\text{Rule } R(j_1, j_2): \quad \text{IF } d_i \text{ is } \text{A}_{j_1} \text{ and } \phi_i \text{ is } \text{B}_{j_2} \text{ then } f_i \text{ is } \text{C}_{(k, l)} \quad \text{(11)}
\]

\[
j_1 \in \{1, 2, 3\}, \quad j_2 \in \{1, 2, 3\}, \quad f(i, j_2) \in \{1, 2, 3\}
\]

\[
\begin{array}{|c|c|c|c|}
\hline
f_i & d_i & \hline
\text{C} & \text{N} & \text{F} \\
\text{N} & \text{B} & \text{B} & \text{N} \\
\text{B} & \text{B} & \text{N} & \text{G} \\
\hline
\end{array}
\]

Table 1. The rule base of the proposed fuzzy system.

That is \( C_{(1,1)} = C_{(1,2)} = C_{(1,3)} = C_{(2,1)} = C_{(2,2)} = \text{B}, \)
\( C_{(2,3)} = C_{(3,1)} = C_{(3,2)} = \text{N}, \) and \( C_{(3,3)} = \text{G} \) in the consequent part of the fuzzy system. The maximal visible distance detected by the scanning lines of vision is about 45 cm. The absolute of the angle difference between the goal direction and the move direction of the robot is from 0° to 180°. So, the universe discourse of the input and output variables are selected by \( d_i \in [0, 45] \), \( \phi_i \in [0, 180] \), and \( f_i \in [0, 100] \). The term sets of the input and output variables are described as follows:

\[
T(d_i) = \{A_1, A_2, A_3\} = \{\text{C, N, F}\} \quad \text{(12)}
\]

\[
T(\phi_i) = \{B_1, B_2, B_3\} = \{\text{S, N, B}\} \quad \text{(13)}
\]

and

\[
T(f_i) = \{C_1, C_2, C_3\} = \{\text{B, N, G}\} \quad \text{(14)}
\]

where the linguistic values of \( A_1, A_2, \) and \( A_3 \) are respectively denoted C (Close), N (Normal), and F (Far) for the input variable \( d_i \). The linguistic values of \( B_1, B_2, \) and \( B_3 \) are respectively denoted S (Small), N (Normal), and B (Big) for the input variable \( \phi_i \). The linguistic values of \( C_1, C_2, \) and \( C_3 \) are respectively denoted B (Bad), N (Normal), and G (Good) for the output variable \( f_i \). The partitions and the shapes of the membership functions are shown in Fig. 12, where the triangular membership functions and fuzzy singleton-type membership function are respectively used for the input and output variables. Therefore, the final output of the fuzzy system can be described by
\[
T_j = \frac{\sum_{i=1}^{k-1} \sum_{j=1}^{k-1} w(j_1, j_2) v(C_{f(j_1, j_2)})}{\sum_{i=1}^{k-1} \sum_{j=1}^{k-1} w(j_1, j_2)}
\]

where \( v(C_{f(j_1, j_2)}) \) is the crisp value of the fuzzy set \( C_{f(j_1, j_2)} \), and \( w(j_1, j_2) \) is the fire strength of the rule \( R(j_1, j_2) \) and can be described by

\[
w(j_1, j_2) = \min(\mu_{A_i}(d_i), \mu_{B_j}(\phi_i))
\]

As described as above, six evaluation values \( f_j, i \in \{1,2,3,4,5,6\} \) for six basic motions can be obtained by the same fuzzy system. Finally, as shown in Fig. 10, the motion with a highest evaluation value will be selected by the proposed method to be the next motion of the robot in each decision. The appropriate motion \( m_k \) is selected by the following rule:

\[
k = \arg \max_{i \in \{1,2,3,4,5,6\}} f_i
\]

If more than two motions have the same highest evaluation value, the next motion of the robot is decided by the following priority: walking more forward \( (m_6) \), walking forward \( (m_3) \), turning left \( 30^\circ \) \( (m_2) \), turning right \( 30^\circ \) \( (m_4) \), slipping left \( (m_5) \), and slipping right \( (m_1) \). In this way, based on the distance \( d_i \) and angle \( \phi_i \) obtained from the scanning lines of vision and the electronic compass, the proposed fuzzy obstacle avoidance method can be design and implemented on a humanoid robot with six motions so that it is a vision-based autonomous humanoid robot.

5. Simulation and Experiment Results

In order to illustrate the proposed design and implementation method is effective for the vision-based autonomous humanoid robot in the obstacle avoidance. A simulative environment of the obstacle avoidance is constructed and shown in Fig. 13, where the width of the robot in the simulation is 100 according to the real width of the robot is 20 cm. That is the scale of the simulation is 5:1. The robot must walk across the simulative field from the starting line to the terminal line and doesn’t touch any obstacles.

![Fig. 13. The diagram of the obstacle field.](image)

The situation of using four IR sensors and fifteen vision scanning lines are presented in Fig. 14. Because the IR sensor can be installed on the left (right) side and the detecting direction is oblique front in the left (right) side, only one IR sensor can obtain the information of the obstacles located at the left (right) and the left (right) oblique for the robot. For the situation of vision scanning line, in order to detect the obstacle located at the left (right) for the robot, the robot must turning left (right) 75°, and only the left (right) scanning line can obtain the information of the obstacle, but the detecting direction is oblique back in the left (right) side. The extra scanning line must be used to detect the obstacle located at the left (right) oblique for the robot. If this paper only uses the same number of the vision scanning lines such
as IR sensors, the fuzzy obstacle avoidance method by using an image sensor can’t present the best effect. So the fifteen vision scanning lines are used to obtain enough information for the fuzzy obstacle avoidance.

Fig. 14. Distributions of detecting lines for IR sensors and webcam.

Four situations are considered in the simulation: (a) Situation 1 with one obstacle, (b) Situation 2 with three obstacles placed in inverse triangle, (c) Situation 3 with five obstacles placed in pentagon, and (d) Situation 4 with five obstacles placed in inverse pentagon. The results of the proposed method are presented in Fig. 15, where the robot can walk across four different environments smoothly and effectively. Similarly in the same simulative environments, the results of the method [16] based on four IR sensors are presented in Fig. 16. We can see that all these two methods can walk across four simulative environments, but the proposed method can accomplish the job by using a less time step as described in Table 2.

From the time step or accomplished path of these simulation results, we can see that Situation 4 is the most difficult obstacle environment. So an obstacle environment such as Situation 4 is built to verify that the proposed method can let the implemented vision-based humanoid robot walk across the obstacle environment successfully. In this practical experiment, some pictures are shown in Fig. 17. We can see that the robot does an appropriate behavior in each step to avoid obstacles and arrive at the terminal line effectively. These processes are described as follows:

(a) ~ (b): the robot executes the motion “walking forward” to approach the first obstacle.

(c) ~ (d): the robot executes the motion “slipping left” to avoid the first obstacle.

(e) : the robot executes the motion “turning left” to avoid the first obstacle.

(f) ~ (g): the robot executes the motion “walking forward” to cross two obstacles.

(h) : the robot executes the motion “turning right” to avoid the obstacle.

(i) : the robot executes the motion “walking forward” to avoid the obstacle.

(j) : the robot executes the motion “turning right” to avoid the obstacle.

(k) ~ (l): the robot executes the motion “walking forward” to cross two obstacles.

(m) : the robot executes the motion “turning left” to avoid the obstacle.

(n) ~ (o): the robot executes the motion “walking forward” to cross two obstacles and arrives at the terminal.

Table 2. Comparison of the time step for simulation results decided by the method [16] based on four IR sensors and the proposed method based on fifteen scanning lines of vision.

<table>
<thead>
<tr>
<th>Situation</th>
<th>The method [16]</th>
<th>The proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>58</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>68</td>
<td>41</td>
</tr>
</tbody>
</table>

Fig. 15. Simulation results decided by the proposed method based on fifteen scanning lines of vision for four situations: (a) Situation 1, (b) Situation 2, (c) Situation 3, and (d) Situation 4.

Fig. 16. Simulation results decided by the method [16] based on four IR sensors for four situations: (a) Situation 1, (b) Situation 2, (c) Situation 3, and (d) Situation 4.

Fig. 17. Some pictures showing the robot’s appropriate behavior in each step to avoid obstacles and arrive at the terminal line effectively.
Fig. 17. Fifteen sequential image stills for a practical experiment of the humanoid robot decided by the proposed method to avoid five obstacles placed in inverse pentagon.

6. Conclusions

A vision-based fuzzy obstacle avoidance method is proposed and implemented on a vision-based humanoid robot with six walking motions so that it can autonomously decide an appropriate motion in each decision and effectively walk through an unknown environment with many obstacles. A vision system is installed on the robot and fifteen scanning lines of vision are proposed to measure the distance between the robot and the obstacle. Some appropriate vision scanning lines are considered for the distance $d_i$ of the $i$-th motion. Based on the obtained information from fifteen scanning lines of vision and electronic compass, only $3 \times 3$ fuzzy rules are used to realize a fuzzy system so that the proposed fuzzy obstacle avoidance method is able to decide an appropriate motion for the next movement of the robot. It also reduces the system complication and increases the realized possibility. From the simulation and practical experiment results, we can see that the robot can not only avoid obstacles successfully but also arrive at the terminal line effectively.

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References


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