OBSTACLE AVOIDANCE FOR AUTONOMOUS MOBILE ROBOTS BASED ON POSITION PREDICTION USING FUZZY INFERENCE

Takafumi Suzuki
Graduate School of Science and Technology, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

Masaki Takahashi
Department of System Design Engineering, Faculuty of Science and Technolog
Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

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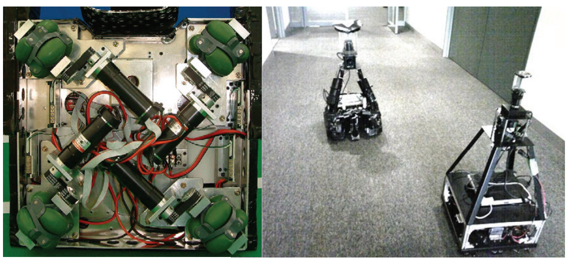
Abstract: This study presents an obstacle avoidance method for Autonomous Mobile Robot by Fuzzy Potential Method (FPM) considering velocities of obstacles relative to the robot. The FPM, which is presented by Tsuzaki, is action control method for autonomous mobile robot. In the proposed method, to decide a velocity vector command of the robot to avoid moving obstacles safely, Potential Membership Function (PMF) considering time until colliding and relative velocity is designed. By means of considering predicted positions of the robot and the obstacle calculated from the time and the relative velocity, the robot can start avoiding behaviour at an appropriate time according to the velocity of the obstacle and the robot. To verify the effectiveness of the proposed method, numerical simulations and simplified experiment intended for an omni-directional autonomous mobile robot are carried out.

1 INTRODUCTION

In the future, it's not difficult to image that we will often come across many autonomous mobile robots traversing densely populated place we live in. In such situation, because the autonomous mobile robots need to carry out their tasks in a place with unknown obstacles, the obstacle avoidance is one of the important functions of the robots. With a view to implementation of autonomous mobile robot working in doors, we employ an omni-directional platform as shown in Figure 1(a). For experimental verification, an omni-directional mobile robot shown in Figure 1(b) is developed. The robot has an omni-directional camera for environmental recognition, and can move to all directions by four omni wheels. While there are many studies about obstacle avoidance method focusing attention on possibility of avoidance, this paper presents the method focusing on not only possibility but also safer trajectory of avoidance. Even if there are the same situations that the robot needs to avoid a static obstacle, timing of beginning avoidance behaviour should vary according to the robot speed. If the obstacles are moving also, the timing should vary according to the velocities of the obstacles. To cite a case, in a situation that a robot and an obstacle go by each other as shown in Figure 2, the robot should avoid along the curved line like (iii) according to the speeds of the obstacle and own speed. To get to the goal with efficient and safe avoidance behaviour in the unknown environment for the robots, predicting the future obstacles' position by their current



(a) (b)

Figure 1: An omni-directional platform of a prototype robot (a) and an example of a situation that the robot needs to avoid the other robot (b).

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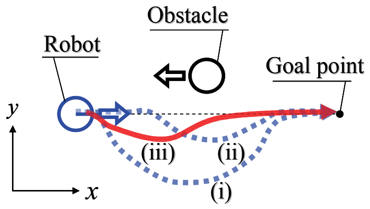


Figure 2: Example of a situation of obstacle avoidance.

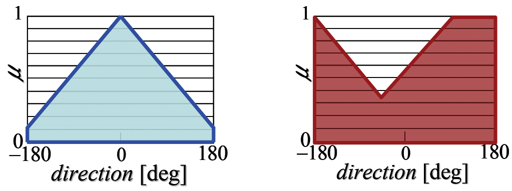


Figure 3: Example of PMF.

movements is needed. This paper introduces a real-time obstacle avoidance method introducing the velocity of obstacle relative to the robot. By means of considering predicted positions of the robot and the obstacle calculated from the time and the relative velocity, the robot can start avoiding behaviour at an appropriate time according to the velocity of the obstacle and the robot. Some researches focus attention on the velocity of obstacle (Ko et al., 1996) to avoid moving obstacles efficiently. In this research, virtual distance function is defined based on distance from the obstacle and speed of obstacle, however, only projection of the obstacle velocity on the unit vector from the obstacle to the robot is considered. In other words, the velocity of the robot is not considered. On the other hand, in (Ge et al., 2002), the velocity of the obstacle relative to the robot is considered. Our approach also employs the relative velocity. In addition to this approach, a position vector of the obstacle relative to the robot in the future is calculated by the relative position and the velocity. To solve the real-time motion planning problem, fuzzy potential method (FPM) is proposed by Tsuzaki (Tsuzaki et al., 2003). In this research, the method is applied to autonomous mobile robot which plays soccer. By adequate designing of potential membership function (PMF), it is realized that wheeled robots can get to the goal with conveying a soccer ball and avoiding obstacles. This method is easy to understand at a glance. However, in dynamic environment, to avoid moving obstacles efficiently, more specific guideline of designing is desired. In this paper, we introduce design method of PMF considering the predicted positions and discuss the availability by comparing the design of PMF considering the relative velocity and that not considering.

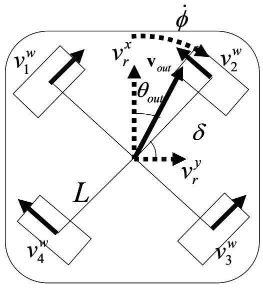


Figure 4: An omni-directional platform.

2 FUZZY POTENTIAL METHOD (FPM) FOR OMNI-DIRECTIONAL PLATFORM

In the Fuzzy Potential Method (FPM), a recent command velocity vector considering element actions is decided. Element actions are represented as Potential Membership Functions (PMFs), and then they are integrated by means of fuzzy inference. Furthermore, by using a state evaluator, the PMFs are modified adaptively according to the situation. The directions on the horizontal axis in Figure 3 correspond to the directions which are from -180 to 180 degrees and measured clockwise from the front direction of the robot. The priority for the direction is represented on the vertical axis. By use of the priority, direction and configured maximum and minimum speed, the current command velocity vector $\mathbf{v}_{out}$ is calculated. The command velocity vector is realized by four DC motors and omni wheels using following equations:

$$v_r^x = \|\mathbf{v}_{out}\| \cos\theta_{out} \tag{1}$$

$$v_r^y = \|\mathbf{v}_{out}\| \sin\theta_{out} \tag{2}$$

$$\begin{pmatrix} v_1^w \\ v_2^w \\ v_3^w \\ v_4^w \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta & L \\ \cos\delta & -\sin\delta & -L \\ -\cos\delta & -\sin\delta & L \\ -\cos\delta & \sin\delta & -L \end{pmatrix} \begin{pmatrix} v_r^x \\ v_r^y \\ \dot{\phi} \end{pmatrix} \tag{3}$$

where $\mathbf{v}_{out}$ and $\dot{\phi}$ are respectively current command velocity vector and rotational speed. δ is an angle of gradient for each wheel. L is a half of a distance between two catawampus wheels. v_i^w is a command movement speed of each i-th wheel.

PMF idea allows us to represent our knowledge and experiences easily, and furthermore it gives us easy understanding. The priority can be seen as a desire for each direction of the robot. In this paper, to discuss an obstacle avoidance problem, methods for generating of PMF to head to the goal and to avoid moving obstacles are introduced. This method has two steps. First step is generating PMFs. Second step is deciding the command velocity vector by use of fuzzy inference to integrate the PMFs. Hereinafter, design method of PMF considering the obstacle velocity relative to the robot and way to decide the command velocity vector by fuzzy inference are described.

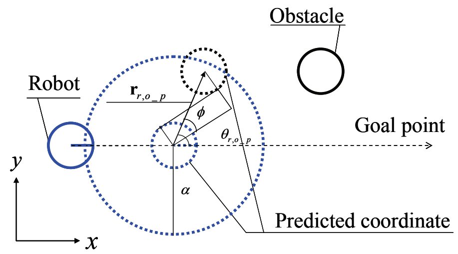


Figure 5: Predicted coordinate.

3 FPM CONSIDERING THE RELATIVE VELOCITY

To realize the obstacle avoidance in dynamic environment, the proposed method employs two different PMFs, one is considering the velocity of obstacle relative to the robot, the other is to head to the goal. PMF is denoted by μ which is function of θ. Note θ is the direction from -180 to 180 degrees measured clockwise from front direction of the robot. To simplify the analysis, it is assumed that the autonomous mobile robots detect obstacles by equipped external sensors and are capable of calculating the positions and velocities of obstacles relative to the robot. The shapes of the robot and the obstacles are treated as circles on 2D surface.

3.1 Design of PMFs

3.1.1 PMF for an Obstacle

To avoid moving obstacles safely and efficiently, an inverted triangular PMF by specifying a vertex, height and base width is generated. Because this PMF considers future positions of the robot and the obstacle, the robot can start avoiding the obstacle early and be prompted not to go on to the future collision position. For the purpose of safe avoidance, the PMF μ_o is generated.

First, to predict the future state of both the obstacle and the robot with the aim of efficient avoidance, a

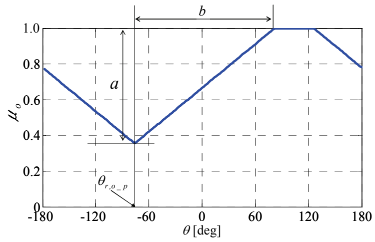


Figure 6: PMF for obstacle considering relative velocity.

predicted relative position vector, in γT seconds, $\mathbf{r}_{r,o\_p} = (\mathrm{r}_{x\_p}, \mathrm{r}_{y\_p})$ is calculated as following equation:

$$\mathbf{r}_{r,o\_p} = \mathbf{r}_{r,o} + \gamma T \mathbf{v}_{r,o} \tag{4}$$

where $\mathbf{r}_{r,o} = (\mathrm{r}_x, \mathrm{r}_y)$ is current position vector of the obstacle relative to the robot, and $\mathbf{v}_{r,o} = (\mathrm{v}_x, \mathrm{v}_y)$ is the current velocity vector of obstacle relative to the robot. γ is an arbitrary parameter from 0 to 1. T ,which is the time until the distance between the obstacle and the robot is minimum, is defined as following equation:

$$T = \frac{\left\|\mathbf{r}_{r,o} - \mathbf{p}\right\|}{\left\|\mathbf{v}_{r,o}\right\|} \tag{5}$$

where $\mathbf{p} = (\mathrm{p}_x, \mathrm{p}_y)$ is a position vector of the obstacle relative to the robot when a distance in the future between the obstacles and the robot is minimum. $\mathbf{p}$ is calculated by means of relative position and velocity vector as following equation:

$$\begin{pmatrix} \mathrm{p}_x \\ \mathrm{p}_y \end{pmatrix} = \begin{pmatrix} \left\{(\mathrm{v}_y/\mathrm{v}_x)\mathrm{r}_y - \mathrm{r}_x\right\} / (\mathrm{v}_y/\mathrm{v}_x + \mathrm{v}_x/\mathrm{v}_y) \\ -(\mathrm{v}_y/\mathrm{v}_x)\mathrm{p}_x \end{pmatrix} \tag{6}$$

As described above, the predicted relative position vector, at the time γT seconds from now, $\mathbf{r}_{r,o\_p}$ is calculated as Figure 3 shows. By use of this position vector, a predicted obstacle direction relative to the robot θ_{r,o_p} is calculated as following:

$$\theta_{r,o\_p} = \arctan\left(\frac{\mathrm{r}_{y\_p}}{\mathrm{r}_{x\_p}}\right) \tag{7}$$

where, θ_{r,o_p} is decided to be the vertex of the inverted triangle.

Next, as a measure to decide how far the robot should depart from the obstacle, a is defined as the height of the inverted triangular PMF. a is described as following equation:

$$a = \frac{\alpha - \left\|\mathbf{r}_{r,o\_p}\right\|}{\alpha - R_{r,o}} \qquad if\ \left\|\mathbf{r}_{r,o\_p}\right\| < \alpha \tag{8}$$

$$R_{r,o} = R_r + R_o \tag{9}$$

where R_r and R_o denote respectively the radius of the robot and that of the obstacle treated as circles. If the calculated obstacle position at γT seconds later is inside of a circle with radius α from the robot position at γT seconds later, the PMF for obstacle avoidance considering the relative velocity is generated. In other words, if a predicted relative distance $\left\|\mathbf{r}_{r,o\_p}\right\|$ is below α , a is defined and the inverted triangular PMF corresponding to the obstacle is generated. Smaller the predicted relative distance is, larger the value of a is.

In addition, a base width of inverted triangular PMF is decided by following equation:

$$b = \eta\left\|\mathbf{v}_{r,o}\right\| + \phi \tag{10}$$

where ϕ is decided based on the sum of radiuses of the robot and the obstacle, and predicted relative position vector as Figure 3 shows. ϕ is calculated by following equation:

$$\phi = \arcsin\left(\frac{R_{r,o}}{\left\|\mathbf{r}_{r,o\_p}\right\|}\right) \tag{11}$$

b increases up to π [rad] in proportion to an absolute value of the relative velocity and predicted relative distance. If the obstacle comes at rapidly, for instance, the value of b increases. Hence, the base width grows shown in Figure 4, and the value of priority for the direction of the obstacle relative to the robot comes about to be reduced. η is a gain.

As mentioned above, by deciding the vertex, the height and the base width of inverted triangle considering the predicted relative position, PMF μ_o , which aims to early starting of avoidance behavior and prompt the direction of the velocity vector to be far from obstacle direction in response to the fast-moving obstacle, is generated.

3.1.2 PMF for a Goal

To head to the goal, a PMF μ_d shaped like triangle as shown in Figure 5. As a measure to decide how much the robot want to head to the goal, c is defined as the height of the triangular PMF. c gets the maximum value at an angle of the goal direction relative to the front direction of the robot, θ_d , and is described as following equation:

$$c = \begin{cases} \dfrac{\left\|\mathbf{r}_{r,d}\right\|}{\varepsilon} & if \quad \left\|\mathbf{r}_{r,d}\right\| \le \varepsilon \\ 1.0 & if \quad \left\|\mathbf{r}_{r,d}\right\| > \varepsilon \end{cases} \tag{12}$$

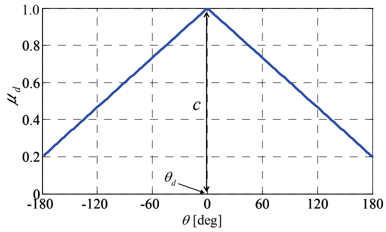


Figure 7: PMF for a goal point.

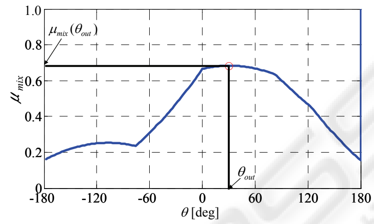


Figure 8: Mixed PMF.

where $\left\|\mathbf{r}_{r,d}\right\|$ is an absolute value of the position vector of the goal relative to the robot. ε is constant. If $\left\|\mathbf{r}_{r,d}\right\|$ is below ε , c is defined. The shorter the distance between the obstacle and the robot is, the smaller c becomes. Therefore the robot can decelerate and stop stably.

3.2 Calculation of Command Velocity Vector by Fuzzy Inference

The proposed method employs fuzzy inference to calculate the current command velocity vector. Specifically, The PMF μ_o , which considers the velocity of obstacle relative to the robot, and the PMF μ_d , which is to head to the goal, are integrated by fuzzy operation into a mixed PMF μ_{mix} as shown in Figure 6. μ_{mix} is an algebraic product of μ_o and μ_d as following equation:

$$\mu_{mix} = \mu_d \cdot \mu_o \tag{13}$$

Finally, by defuzzifier, the command velocity vector is calculated as a traveling direction θ_{out} and an absolute value of the reference speed of the robot base on the mixed PMF μ_{mix} . θ_{out} is decided as the direction θ_i which makes a following function $f(\theta)$ maximum.

$$f(\theta) = \sum_{i=j-n}^{j+n} \mu_{mix}(\theta_i) \tag{14}$$

where n is the parameter to avoid choosing undesirable θ_i caused by such as noises on the

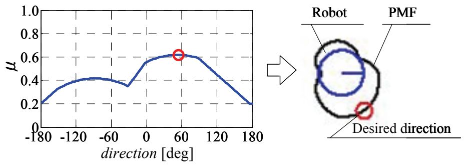


Figure 9: Visualization of PMF.

sensor data. Based on θ_{out}, v_{out} is calculated as following equation:

$$v_{out} = \mu_{mix}\left(\theta_{out}\right)\left(v_{max} - v_{min}\right) + v_{min} \qquad (15)$$

where $\mu_{mix}\left(\theta_{out}\right)$ is the mixed PMF μ_{mix} corresponding to the θ_{out}, v_{max} and v_{min} are configured in advance respectively as higher and lower limit of the robot speed.

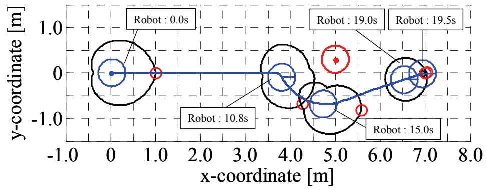
3.3 Visualization for PMF on Two-dimension Surface

It would be convenient to have a visualizer that show us why the robot will go on to the direction. In the proposed method, we can see aspects of the PMF on two dimension surface and understand easily the reason for choice of the direction. For example, a PMF described on polar coordinate shown in Figure 9(a) is comparable to the PMF described on x-y coordinate shown in Figure 9(b).

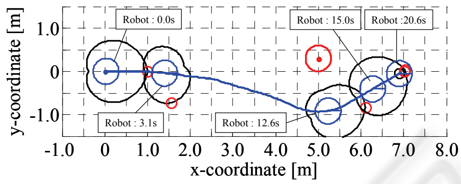
4 SIMULATION RESULTS

The radius of robot and obstacle are supposed to be both 0.3m, therefore, $R_{r,o} = 0.6\text{m}$. α in equation (8) is 1.6m. γ in equation (4) is 0.7. ε in equation (12) is 1.0m.

Figure 10, 11 and 12 show the simulation results when the robot passes the obstacle. Initial positions of the robot and the obstacle are respectively $(0\text{m}, 0\text{m})$ and $(5.0\text{m}, 0.3\text{m})$. The goal position of the robot is $(7.0\text{m}, 0\text{m})$. In the situation in Figure 10, the higher limit of robot speed is $v_{\max} = 0.5\text{m/s}$, the lower one is $v_{\min} = 0.0\text{m/s}$. The higher limit of acceleration of the robot is $a_r = 1.0\text{m/s}^2$. The simulations have done with three different obstacle speed $v_o = 0.0, 0.5\text{m/s}$, that the direction is negative on x-axis. Figure 10(a) and (b) show respectively the trajectory of the robot that the PMF for obstacle avoidance is generated without considering the relative velocity and that with considering the relative velocity, when $v_o = 0.0\text{m/s}$. In Figure 10(a),



(a) not using PMF considering relative velocity



(b) using PMF considering relative velocity

Figure 10: Simulation results of an obstacle avoidance going by each other when speed of obstacle (v_o) is 0.0m/s and of a robot (v_r) is 0.5m/s.

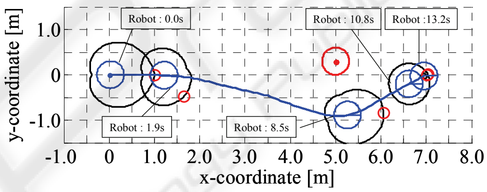
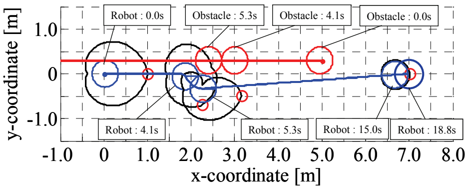


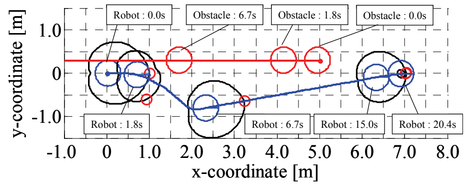
Figure 11: Simulation results of an obstacle avoidance going by each other when speed of obstacle (v_o) is 0.0m/s and of a robot (v_r) is 0.8m/s.

the robot gets close to the obstacle because the relative velocity is not considered. On the other hand, in Figure 10(b), the early starting of avoidance behaviour due to generating PMF by use of predicted information based on the relative velocity. In addition to the situation as in Figure 10(b), in Figure 11, the higher limit of the robot speed has been changed: $v_{\max} = 0.8\text{m/s}$. Even if the robot speed becomes more rapid, the robot succeed in efficient avoidance. In Figure 12(a) and (b), the trajectories of the robot, with PMF considering the relative velocity and not considering that, when the obstacle speed $v_o = 0.5\text{m/s}$. In (a), due to delay of starting avoidance behaviour, the robot collided with the obstacle. On the other hand, in (b), due to the early starting of the avoidance behaviour, the robot succeeded at the obstacle avoidance.

From these simulation results, it is confirmed that by an associating the PMF for avoidance with the relative velocity, faster the obstacle speed is, earlier the timing of the avoidance behaviour of the robot is, therefore the ability of avoiding obstacle can be enhanced.



(a) not using PMF considering relative velocity



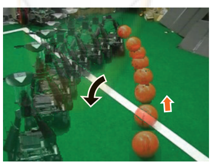
(b) using PMF considering relative velocity

Figure 12: Simulation results of obstacle avoidance going by each other when speed of an obstacle (v_o) is 0.5m/s and of a robot (v_r) is 0.5m/s.

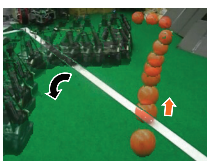
5 EXPERIMENTAL RESULTS

To verify the effectiveness of the proposed method that employs PMF considering the velocity of the obstacle of the robot, a ball is supposed to be a moving obstacle and is rolled toward the robot. The robot recognizes the environment by the omni-directional camera. A position of a goal and that of an obstacle relative to the robot are calculated by extracting features based on objects' colours. The robot size is L 0.4 × W 0.4 × H 0.8m and the ball diameter is 0.2m. The radius of robot and obstacle are supposed to be 0.3m and 0.1m respectively, therefore, $R_{r,o} = 0.4\text{m}$. α is set to 1.4m when the robot uses the proposed PMF which is considering relative velocity. When the robot doesn't use the proposed PMF, α is set to 2.4m. γ is 0.7. ε is 1.0m. $v_{\max}$ is 0.5m/s, $v_{\min}$ is 0.0m/s. a_r is 1.0m/s^2 .

When the robot used the proposed PMF, which was considering relative velocity, as shown in Figure 13 (a), it succeeded in avoiding the moving ball with smooth trajectory. On the other hand, in the situation Figure 13 (b), the robot with the PMF, which was not considering relative velocity, diverged once.



(a)



(b)

Figure 13: Trajectories of the obstacle (ball) and the robot with the PMF considering relative velocity (a) and not considering relative velocity (b).

6 CONCLUSIONS

In this paper, design method of the potential membership function (PMF), which is considering the velocity of the obstacle relative to the robot for the purpose of avoiding the moving obstacle safely and smoothly, has been presented. In the proposed method, the proposed PMF for an obstacle and PMF for a goal are unified by fuzzy inference. By defuzzification, the command velocity vector of the robot is calcu lated and the obstacle avoidance has realized. A numerical simulation, which assumes an obstacle avoidance of autonomous omni-directional mobile robot, has done. As the result of the comparison between the design method of PMF using relative velocity and not using, it is confirmed that the ability of avoiding the moving obstacle can be enhanced. In addition, thorough simplified experiments, the real robot can avoid an obstacle using proposed method.

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