Simultaneous Control of Translational and Rotational Motion for Autonomous Omnidirectional Mobile Robot Considering Shape of the Robot and Movable Area by Heights

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Abstract. This paper presents a real time collision avoidance method for an autonomous omnidirectional mobile robot considering shape of the robot and movable area by heights based on simultaneous control of translational and rotational motion. Service robots which have been developed in recent years have arms to work and execute tasks. In these robots, the size of width is sometimes not equal to that of depth by heights. In order to avoid obstacles considering safety and mobility for the robots, it is necessary to evaluate shape of the robot and movable area by heights. To evaluate them, the robot model is defined by heights. Evaluating of the robot model and the movable area for each height, if the robot is unable to move keeping a safe distance from the obstacles, the robot determines the suitable orientation angle considering the minimum length from the center of the robot model to that outer shape. In this paper, the novel control method based on the fuzzy potential method is presented. To verify the effectiveness of the proposed method, several numerical simulations are carried out.

Keywords: Autonomous mobile robot, Obstacle avoidance, Omnidirectional platform, Fuzzy potential method.

1 Introduction

Recently, autonomous mobile robots work in human living space have been studied and developed. Some cases of these robots installation to public facilities have been reported [1-3]. These robots sometimes have two arms mounted on a torso so these robots can be used for manipulation, whole-body activities, and human-robot interaction [4, 5]. In these robots, the size of width is not equal to that of depth by heights. In order to avoid obstacles considering safety and mobility, it is necessary to evaluate shape of the robot and movable area by heights.

Various obstacle avoidance methods and their availabilities for mobile robots have described [1-3, 6-8]. Most of these studies regard the robots as points or circles and control methods of the translational movements in two-dimensional plane are

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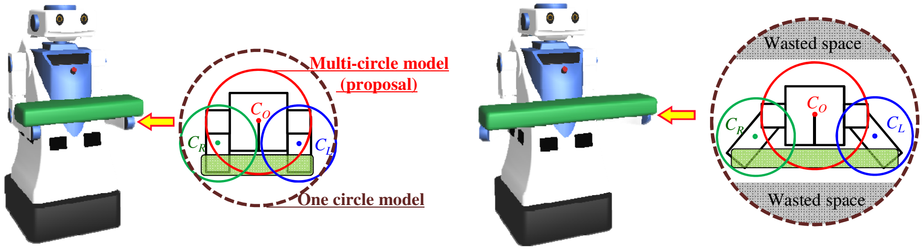
discussed. In these studies, a non-circle robot is regarded as a circle robot with consideration of maximum size of the robot. However, depending on the shape of the robot such as horizontally long shape, this approach reduces and wastes available free space and can decrease the possibility that the robot reaches the goal. To enable wide robots to avoid obstacles safely and efficiently, it is necessary to control not only a translational motion but also a rotational motion. Several studies have focused on the orientation angle of the robot [9, 10]. However, these methods require an environmental map and the studies have not shown the effectiveness for avoidance of unknown obstacles by autonomous mobile robots. Therefore, in our current research, to avoid unknown obstacles reactively for wide robots, simultaneous translational and rotational motion control method is presented [11]. In addition, there are obstacles of various heights in the human living space and the relation between the robot and the surrounding environment varies depending on shape of the robot. Therefore, in order to avoid obstacles more safely and efficiently, it is necessary to evaluate cross-sectional shape of the robot and movable area by heights.



(a) (b)

Fig. 1. Two robot models considering cross-sectional shape of the robot at the height of arms: (a) robot holds a short baggage, (b) robot holds a long baggage

Consequently, this study proposes the following two points.

I. Robot model considering cross-sectional shape of the robot.
II. Simultaneous control of translational and rotational motion considering shape of the robot and movable area by heights.

With the proposed method, if the robot is unable to move keeping a safe distance from the obstacles, the robot determines the suitable orientation angle considering the minimum length from the center of the robot to that outer shape in real time. To verify the effectiveness of the proposed method, several simulations are carried out.

2 Robot Model Considering Cross-Sectional Shape of the Robot

Service robots sometimes use the arms to transport baggage. In that case, the robot size of width is not equal to that of depth by heights. If these wide robots are modeled as a circle, the robots decrease the possibility to reach the goal because of wasting available free space. In order to achieve obstacle avoidance considering safety and mobility, it is necessary to introduce a robot model considering cross-sectional shape. In this study, to consider the changes of the shape of the robot as shown in Fig. 1, a new robot model with multi-circle is proposed. The modeling method is as follows.

- Robot body is enclosed in a circle.
- If the parts such as arms that cannot be enclosed in the body circle exist, these are enclosed in each circle.

As shown in Fig. 1, the proposed robot model is available to change the angle of the arms according to the size of baggage that the robot holds.

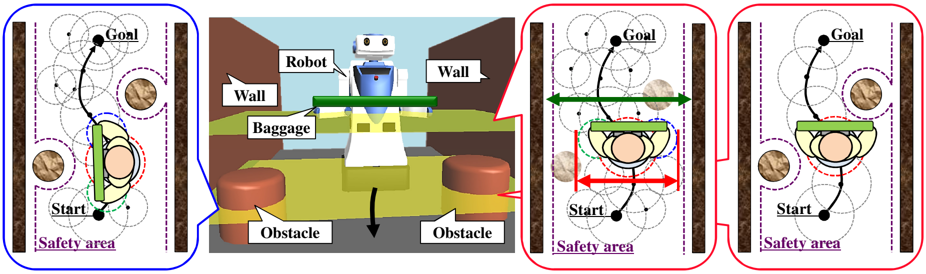


Fig. 2. Trajectories of the robot with two motion control method: (*left*) considering footprint at the height of wheeled platform, (*right*) evaluating cross-sectional shape of the robot and movable area by heights

3 Simultaneous Control of Translational and Rotational Motion Considering Shape of the Robot and Movable Area by Heights

For the robot that the size of width is not equal to that of depth by heights, simultaneous translational and rotational motion control method is presented [11]. In addition to the shape of the robot is different by heights, there are obstacles of various heights the human living space. For example, in situation as shown in Fig. 2, considering the shape of the robot by heights, it is able to move keeping a safe distance from obstacles without rotational motion. Therefore, in order to avoid obstacles safely and efficiently, it is necessary to evaluate cross-sectional shape of the robot and the movable area by heights. In this study, evaluating shape of the robot and movable area by heights, if the robot is unable to move keeping a safe distance from the obstacles, the robot determines the suitable orientation angle considering the minimum length from the center of the robot to that outer shape. Then, evaluation of the shape of the robot and the movable area is used the width of the robot model and the movable area measured with range sensor like Laser Range Finder (LRF) by heights.

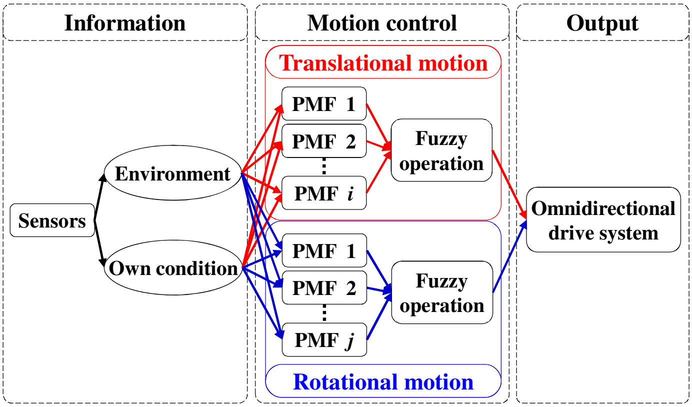


Fig. 3. Concept of fuzzy potential method for simultaneous translational and rotational motion with an omnidirectional platform

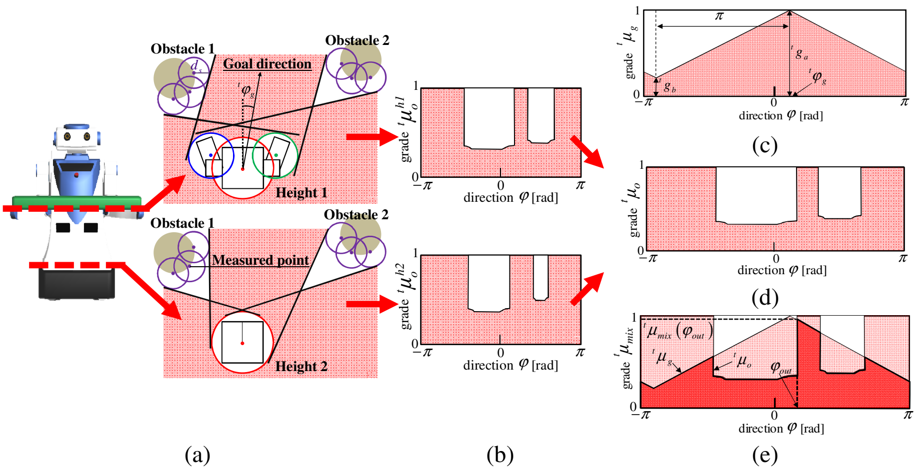


Fig. 4. An example of determination of translational motion: (a) situation of the robot and the environment, (b) PMFs for obstacles in each height, (c) PMF for a goal, (d) integrated PMF for obstacles, (e) mixed PMF for translational motion

In this study, the novel control method based on the fuzzy potential method (FPM) [12] with proposed model is presented. Fig. 3 shows a concept of the FPM that takes into consideration both translational and rotational motion by heights. In the FPM, a command velocity vector that takes into consideration element actions is decided. Element actions are represented as potential membership functions (PMFs), and then they are integrated by means of fuzzy inference. The horizontal axis of PMF is directions which are from $-\pi$ to π radians measured clockwise from the front direction of the robot. The vertical axis of PMF is the grade for the direction. The grade, direction, and configured maximum and minimum speeds, are used to calculate the command velocity vector. Finally, translational and rotational velocity commands, which are calculated by defuzzification of mixed PMFs, are realized by an omnidirectional drive system.

3.1 Translational Motion Considering Shape of the Robot and Environment by Heights

For the robot shown in Fig. 4(a), to generate translational PMF for moving toward the goal keeping the safe distance d_s from obstacles that detected in each height.

3.1.1 PMF for a Goal

To head to the goal, a triangular PMF ${}^t\mu_g$ is generated, as shown in Fig. 4(c). As a measure to decide how close to the goal the robot should go, ${}^tg_a$ is defined as the height of the triangular PMF. As a measure to decide how much the robot can back away from obstacles, ${}^tg_b$ is defined. ${}^t\mu_g$ reaches the maximum value as ${}^tg_a$ at an angle of the goal direction relative to the front direction of the robot ${}^t\varphi_g$.

$$ {}^tg_a = \begin{cases} \dfrac{\left\| \mathbf{R}_{r,g} \right\|}{\varepsilon} & if\ \left\| \mathbf{R}_{r,g} \right\| \le \varepsilon \\ 1.0 & otherwise \end{cases}. \tag{1} $$

$$ {}^tg_b = \eta\,{}^tg_a \qquad (0.0 \le \eta < 1.0). \tag{2} $$

where $\left\| \mathbf{R}_{r,g} \right\|$ is an absolute value of the position vector of the goal relative to the robot. ε and η are constants. If $\left\| \mathbf{R}_{r,g} \right\|$ is below ε, ${}^tg_a$ is defined.

3.1.2 PMF for Obstacles

To avoid obstacles safely and efficiently in real time, a concave shaped PMF ${}^t\mu_o^{hi}\ (hi : height\, i = 1, 2, \cdots, n)$ are generated. These PMFs are specified by depth and width, which are calculated based on the geometrical relation between obstacles and the robot in each heights as shown in Fig. 4(b). Then, they are all integrated to ${}^t\mu_o$ shown in Fig. 4(d) by calculating the logical product.

$$ {}^t\mu_o = {}^t\mu_o^{h1} \wedge {}^t\mu_o^{h2} \wedge \cdots \wedge {}^t\mu_o^{hn}. \tag{3} $$

3.1.3 Calculation of a Translational Command Velocity Vector

The PMF ${}^t\mu_{mix}$ for translational motion is generated and calculate the command velocity vector. ${}^t\mu_{mix}$ in Fig. 4(e) is an logical product of ${}^t\mu_g$ and ${}^t\mu_o$. By defuzzifier, a velocity command vector is calculated as a traveling direction φ_{out} and an absolute value of the reference speed of the robot based on the mixed PMF ${}^{t}\mu_{mix}$. φ_{out} is decided as the direction that makes the PMF ${}^{t}\mu_{mix}(\varphi)$ maximum. Based on φ_{out}, v_{out} is calculated as follows.

$$v_{out} = {}^{t}\mu_{mix}(\varphi_{out})(v_{max} - v_{min}) + v_{min}. \tag{4}$$

where ${}^{t}\mu_{mix}(\varphi_{out})$ is the mixed PMF for translational motion correspond to the φ_{out}. v_{max} and v_{min} are respectively the upper and lower limits of the robot speed.

3.2 Rotational Motion Based on the Evaluation of the Shape of the Robot and the Movable Area by Heights

PMF for rotational motion based on the evaluation of the shape of the robot and the movable area by heights is generated.

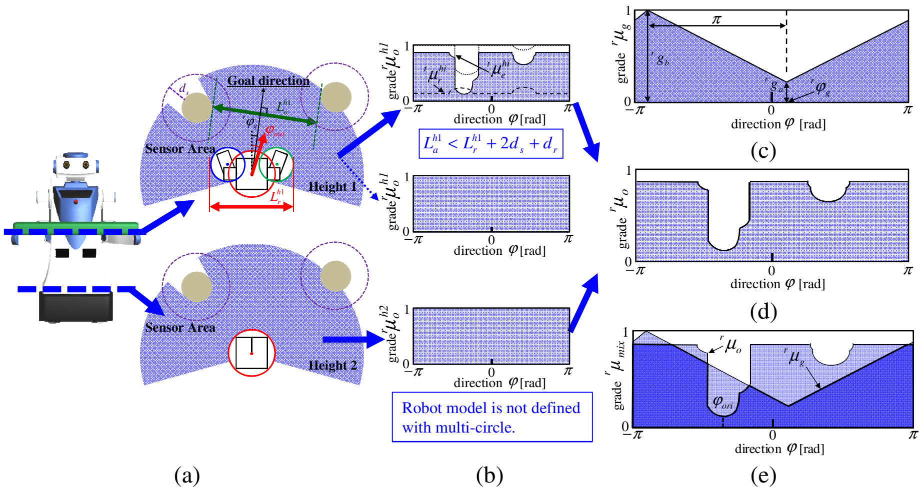


Fig. 5. An example of determination of rotational motion: (a) situation of the robot and the environment, (b) PMFs for obstacles in each height, (c) PMF for a goal, (d) integrated PMF for obstacles, (e) mixed PMF for rotational motion

3.2.1 PMF for a Goal

In order to turn the front of the robot toward the goal direction or the travelling direction if there is no obstacle to avoid, PMF for a goal is generated as ${}^{r}\mu_{g}$ shown in Fig. 5(c). This shape is decided in same way as ${}^{t}\mu_{g}$.

3.2.2 PMF for Obstacles

If the robot is unable to move keeping the safe distance d_s from the obstacles with facing the goal direction or the travelling direction, the PMF ${}^{r}\mu_{o}$ to determine the suitable orientation angle considering the minimum length from the center of the robot model to that outer shape is generated. To evaluate the shape of the robot and the movable area, the robot width L_r^{hi} and the movable area width L_a^{hi} are calculated at the height that the robot model defined multi-circle. As shown in Fig. 5(a), L_a^{hi} are the vertical distances between the obstacles detected in the travelling direction. To determine whether the robot is able to move keeping the distance d_s from the obstacles with facing the goal direction is used follow equation.

$$L_a^{hi} < L_r^{hi} + 2d_s + d_r. \tag{5}$$

where d_r is the parameter to avoid determining to be unnecessary rotational motion for obstacles even if that is required due to measurement error. Accordingly, the PMF for rotational motion considering obstacles is as follows.

$${}^r\mu_o^{hi}(\varphi) = \begin{cases} {}^r\mu_e^{hi}(\varphi) - {}^r\mu_r^{hi}(\varphi) & \text{if Multi-circle model and Formula (5)} \\ 1.0 & \text{otherwise} \end{cases}. \tag{6}$$

${}^r\mu_e^{hi}(\varphi)$ are generated based on the distance from the center of the robot to obstacles, as shown in Fig. 5(b). The relative distances are obtained with range sensor such as LRF. Then, they are all integrated to ${}^r\mu_o$ shown in Fig. 5(d) by calculating the logical product in same way as ${}^t\mu_o$.

3.2.3 Calculation of a Rotational Command Velocity Vector

For the rotational motion, like the translational motion, the rotational command velocity vector is derived. The PMFs ${}^r\mu_g$ and ${}^r\mu_o$ are integrated by fuzzy operation into a mixed PMF ${}^r\mu_{mix}$, as shown in Fig. 5(e). By defuzzifier, the command velocity vector is calculated as a rotational direction φ_{ori} and an absolute value of the reference speed of the robot. φ_{ori} is decided as the direction that makes the following function $h(\varphi)$ minimum.

$$h(\varphi) = \int_{\varphi-\zeta}^{\varphi+\zeta} {}^r\mu_{mix}(\psi)\,d\psi. \tag{7}$$

where ζ is the parameter to avoid choosing an uncertainty φ caused by, for example, noise on the sensor data. Based on φ_{ori}, ω is calculated as follows.

$$\omega = \frac{\varphi_{ori}}{\pi}(\omega_{max} - \omega_{min}) + \omega_{min}. \tag{8}$$

ω_{max} and ω_{min} are the upper and lower limits of the robot rotational speed.

Finally, translational and rotational velocity commands are realized simultaneously by an omnidirectional drive system [11].

4 Simulation

In simulation, to verify the effectiveness of the proposed robot model and motion control method, the situation that the robot transports baggage with arms was assumed.

4.1 Situation of Simulation

The robot has an omnidirectional drive system, and can measure 4.0 m in ±120deg range at 0.23 m height of the wheel platform and 0.60 m height of arms with two LRFs. A safe distance d_s is 0.20 m and complement measurement error parameter d_r is 0.20 m. As shown in Fig. 6, there are two static obstacles (obstacle 1: 0.50×0.60×0.80 m, obstacle 2: 0.50×0.60×0.40m) in the passage of 2.3 m width. However, the robot is assumed to have no priori information about these obstacles.

In situation A, the robot determines the translational motion with one circle robot model. In situation B, the robot determines translational and rotational motion considering the footprint at the height 2. In situation C, the robot determines the suitable orientation angle based on the evaluation of the shape of the robot and

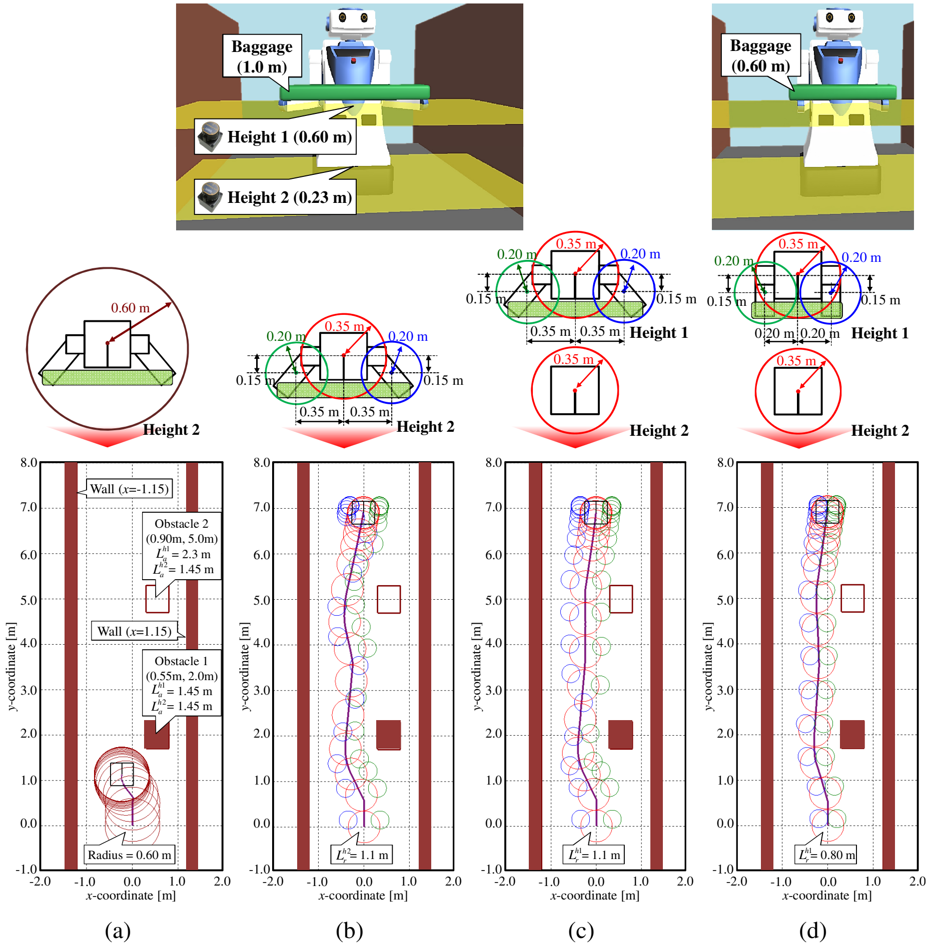


Fig. 6. Simulation results; robot models and trajectories of the robot: (a) situation A, (b) situation B, (c) situation C, (d) situation D

movable area by heights (proposal). In situation D, the position of the arms is different from other situations A-C according to the size of baggage.

4.2 Performance of Multi-circle Robot Model

In situation A shown in Fig. 6(a), the robot regarded as one circle did not get to the goal because the robot model is larger than the movable area next to the obstacle 1 $L_a^{h2}\left(=1.45\,\mathrm{m}\right) < L_r^{h2} + 2d_s\left(=1.6\,\mathrm{m}\right)$. On the other hand, in situation B shown in Figs. 6(b) and 7, the robot modeled with multi-circle was able to pass the obstacle 1 with rotational motion considering the minimum length from the center of the robot to that outer shape. Moreover, in situation D shown in Figs. 6(d) and 7, the robot was able to pass the obstacle 1 without rotational motion because the relation between the robot and the movable area is $L_a^{h2}\left(=1.45\,\mathrm{m}\right) > L_r^{h2} + 2d_s + d_r\left(=1.4\,\mathrm{m}\right)$.

These results show that defining the robot model with multi-circle, it is possible to respond flexibly to the changes of the cross-sectional shape of the robot and design simultaneous control of translational and rotational motion based on the evaluation of the cross-sectional shape of the robot and movable area.

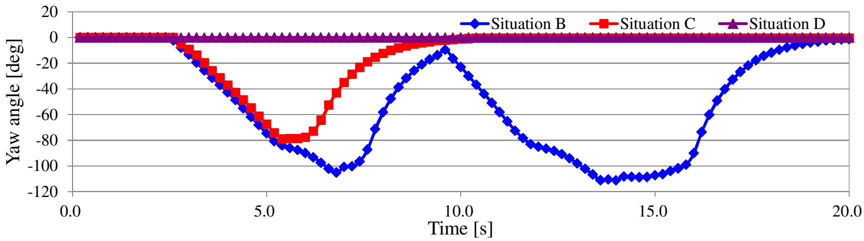


Fig. 7. Time history of yaw angle of the robot in situations B-D

4.3 Performance of Motion Control Based on the Evaluation of the Shape of the Robot and the Movable Area by Heights.

In situation B shown in Figs. 6(b) and 7, the robot changed yaw angle for the obstacle 2 which can be avoided without rotational motion because the robot does not evaluate the shape of the robot and the movable area by heights. On the other hands, in situation C shown in Figs. 6(c) and 7, the robot has achieved to avoid the obstacle 2 without rotational motion depend on the evaluating of the shape of the robot and the movable area by heights $L_a^{h1}\left(=2.3\,\mathrm{m}\right) > L_r^{h1} + 2d_s + d_r\left(=1.7\,\mathrm{m}\right)$. In addition, as shown in Fig. 7, after the rotational motion for the obstacle 1, the robot was able to quickly return to the goal direction, so it is more expected to respond quickly to obstacles in proposed method.

These results show that the evaluation of the cross-sectional shape of the robot and the movable area by heights to the robot which the size of width is not equal to that of depth by heights, the robot can decide the suitable orientation angle according to the situation. As a result, the robot can get to the goal point safely and smoothly.

5 Conclusion

In this paper, toward the realization of motion control for autonomous mobile robots that can be flexible in various situations, the real time collision avoidance method with simultaneous control of translational and rotational motion considering the shape of the robot and the movable area by heights has been proposed. This method used an omnidirectional platform for the drive system and was based on the fuzzy potential method. Evaluating of the cross-sectional shape of the robot and the movable area by heights, if the robot is unable to move keeping a safe distance from the obstacles, the robot determines the suitable orientation angle considering the minimum length from the center of the robot model to that outer shape. The effectiveness has been verified by numerical simulations. It has been shown that the proposed method performs translational and rotational movement simultaneously according to the situation.

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