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Design and Control of Mobile Robot with Mecanum Wheel

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Abstract: In this paper, we present a design of an omni-directional mobile robot with Mecanum wheel and suggest a control method using the fuzzy technique. Our previous version of the mobile robot can be unstable due to the characteristics of the custom-designed Mecanum wheel or to the unexpected effect by suspension. To remedy these defects, we propose a new version of the custom-designed Mecanum wheel and a new structure design of mobile robot. To improve the performance of the robot we implemented a motor control algorithm using the fuzzy gain tuning scheme. The experimental results indicate that the developed holonomic mobile robot is better in performance than the previous robot.

Keywords: Mobile robot, mecanum wheel, omni-directional robot, fuzzy system

1. INTRODUCTION

The omni-directional mobile platform has the advantages over the conventional mobile one in terms of mobility particularly in congested environments, for example, factories, offices, hospitals and elderly care facilities. The special wheels and structure are needed for the mobile robot to have the omni-directional maneuverability. Three wheel structure using 'Omni-wheel' and four wheel structure using 'Mecanum wheel' are the representative examples of the omni-directional platforms. Especially, the omni-directional mobile platform with Mecanum wheels is used in case of requiring the stability of movement like as the fork lift, the wheelchair and so on.

Our omni-directional mobile robot is originally developed as the mobile base for Mobile Haptic Interface (MHI) [1] - [3]. MHI refers to a desktop haptic interface mounted on a mobile base. It can provide an unlimited haptic workspace by autonomously moving the mobile base to a location where a user wants to interact with virtual objects using the force-feedback Haptic interface. To cope with the MHI user's arbitrary motion, the mobile base must be able to change its direction of motion as quickly as possible. For this reason, we designed the omni-directional mobile robot with the rectangular arrangement of four custom-made Mecanum wheels. Our previous mobile robot achieved the aim of the construction of the mobile base with the omni-directional maneuverability for MHI. However, we found the weak points of the robot on user's convenience, the stability of the mobile robot's movement and so on. So we designed the new version of Mecanum wheel and the omni-directional mobile robot to adjust these defects.

In terms of the mobile robot's control, we implemented the motor control algorithm using the conventional PID controller at the previous robot. However, the PID gain tuning by trial and error can be time-consuming and moreover it does not guarantee finding the optimal gains. To overcome these weaknesses we embody the PID gain scheduling method using the fuzzy system in the motor control algorithm. Through the experiment of the mobile robot control, the new control algorithm was compared with the previous control algorithms.

The remainder of this paper is organized as follows. Section 2 introduces the new designed Mecanum wheel, and Section 3 shows the structure of the mobile robot. Section 4 describes the PID gain scheduling method using the fuzzy system, followed by performance evaluation in Section 5. Finally, we conclude this paper in Section 6.

2. WHEEL DESIGN

Our robot uses the special wheel, called Mecanum wheel, to accomplish the omni-directional movement. Swedish inventor, Bengt Ilon, came up with the idea in 1973 when he was an engineer with the Swedish company Mecanum AB. The Mecanum wheel has the free-rolling sub-wheels positioned at an angle offset from the wheel rotation around its circumference. This special characteristic of the wheel allows sideways movements by spinning wheels on the front and rear axles in opposite directions. Forward and backward movements are the same as the conventional wheels. By compounding these movements we can control the mobile robot at any desired direction at any time [4], [5].

Our previous robot has four Mecanum wheels and each wheel consists of six sub-wheels. Because the gap between the adjacent sub-wheels can cause the unstability of mobile robot control, it needs to be reduced. So we designed a new wheel that has bigger diameter and sixteen sub-wheels.

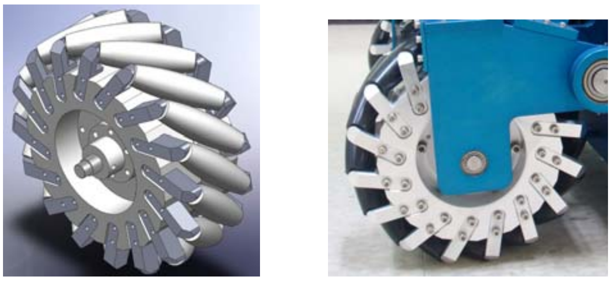

Fig. 1 New version of Mecanum wheel (left : CAD design, right : prototype)

Here, we enumerate the design parameters of the new Mecanum wheel except the design process.

• The number of sub-wheels: $n = 16$.
• The angle between the axis of the sub-wheel and the driving axis: $\eta = 45°$.
• The radius of the whole Mecanum wheel: $R_{Wheel} =$ 103 mm.
• The radius of the sub-wheel: $r_{Rol} = 12$ mm.
• The overlap angle between two neighbor sub-wheels: $\theta_t = 10°$.
• The radius of the sub-wheel axis: $\alpha = 8.5$ mm.

From the above parameters, the radius of sub-wheel from the axle side d and the length of sub-wheel L became $16.5024mm$ and $75.0214mm$, respectively. These values satisfy constraints that must be fulfilled to complete the desired design of Mecanum wheel. More details about designing Mecanum wheel are presented in [2] and [6].

3. ROBOT STRUCTURE

The structure of our robot with Mecanum wheel is rectangular. To control the robot at our will, four contact points between wheels and the ground must be kept always. So we install the suspension system using the spring. Our previous robot do have the suspension system, but its structure can cause uneven force due to two springs. So the new version of the robot comes with the suspension system with only one spring whose structure is designed to decrease its influence on the robot motion.

Because our goal is to develop the appropriate mobile base for MHI, the mobile robot is needed to be more compact for user's convenience. So it is essential in designing the structure of robot to develop more compact mobile robot than the previous version. To do this, we reinforce the part of fixing the wheel set and install the suspension system consisting of one stronger spring. Because it is hard to reduce the size of the mobile robot using the direct connection type between the motor and wheel, we design the motor part using the orthogonal connection type with the miter gear. As a result, the width, length, and height are $552mm$, $615mm$, and $935mm$, respectively. These values show that the new mobile robot is more compact than the previous. The weight is about $90kg$ [2].

The new robot also consists of five main parts: mobile base (including the four suspension sets, 4 Mecanum wheels, 4 geared DC motors, and batteries), driving control box (including a DSP control board and 5 motor drivers), a laptop, a desktop 3 degrees of freedom haptic interface (PHANToM Premium 1.5A; SensAble inc., USA; not in the picture), and a linear unit that has about $400mm$ stroke (see Fig. 2. This new robot has several improvements: the installation position of the haptic device for the user to feel comfortable and the unified structure between the driving control box and the linear unit to improve the stability. Moreover, the user can easily know the state of the mobile robot through the tower LED. The motor torque and the encoder's CPT (count per turn) have been changed because wheel diameters are enlarged to remedy the previous robot's defects. To increase the torque we changed the gear ratio of the gearhead from $53:1$ to $113:1$ at the same motor. The double length of the wheel diameter doubles the moving distance per turn. So to control the mobile robot with similar resolution, we alter the CPT of optical encoder from 512 to 1024.

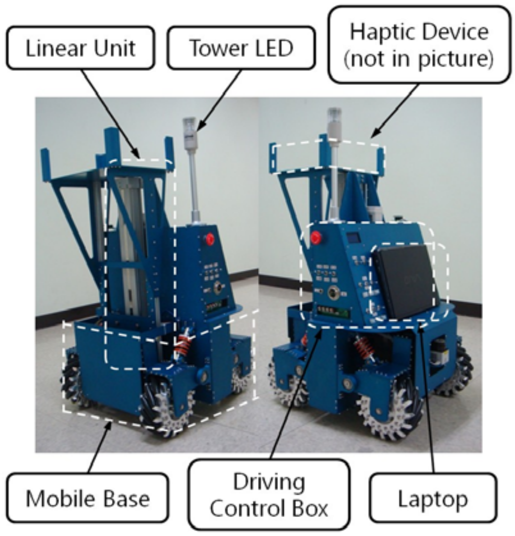

Fig. 2 New design of mobile robot.

4. CONTROL ALGORITHMS

We evaluate three algorithms (Algorithm 1, 2, 3) for motor control. Algorithm 1 and Algorithm 2 in [2] use the PID control with the fixed gains. Algorithm 1 is the conventional PID control that generates the control input using the error between the desired velocity and the current velocity (see Fig. 3). To improve the performance of Algorithm 1, Algorithm 2 considers the position error at the previous control time step when it produces the current control input (see Fig. 4). Further details for Algorithm 1 and 2 can be found in [2].

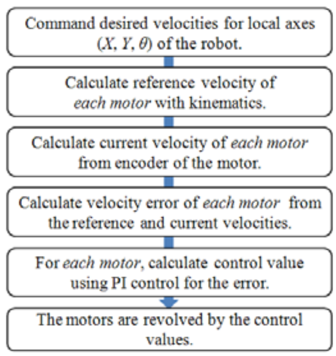

Fig. 3 Block diagram for Algorithm 1.

In this paper, we apply the PID control algorithm whose parameters are tuned by a fuzzy system (Algorithm 3) [7], [8]. The general equation of the discrete-time PID controller is written as

$$u(k) = K_p e(k) + K_i T_s \sum_{i-1}^{k} e(i) + \frac{K_d}{T_s} \Delta e(k).$$

The actually implemented form, the incremental PID

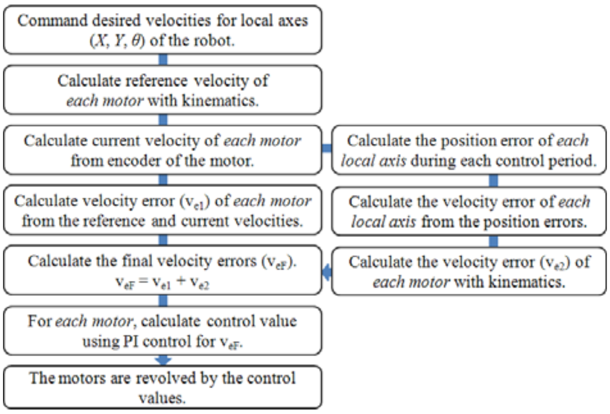

Fig. 4 Block diagram for Algorithm 2.

control function, is given as

$$u(k) = u(k-1) + K_p(e(k) - e(k-1))$$
$$+ K_i T_s e(k) + \frac{K_d}{T_s}\{e(k) - 2e(k-1) + e(k-2)\}.$$

Here, $u(k)$ is the control input signal, $e(k)$ is the error between the desired and current process output at the control time step k, T_s is the sampling period for the controller, and $\Delta e(k) = e(k) - e(k-1)$. The parameters of the PID controller K_p, K_d, and K_i are adjusted to generate the various response curve at the given system. However, it is difficult to find the values of parameters which make the given system show the best performance. So we apply and test the on-line gain scheduling scheme of the PID controller based on fuzzy rules, Algorithm 3, to our new robot. Fig. 5 shows

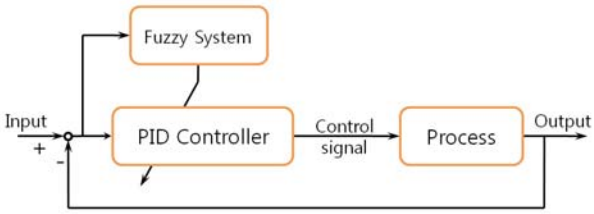

Fig. 5 PID controller with fuzzy system.

the block diagram of the PID controller using the fuzzy system. The main concept of Algorithm 3 is to find the optimal value of controller's parameter using fuzzy system. The following describes the procedure of Algorithm 3. First of all, we assume that K_p, K_d, and K_i have the ranges $[K_{p.\min}, K_{p.\max}]$, $[K_{d.\min}, K_{d.\max}]$, and $[K_{i.\min}, K_{i.\max}]$, respectively. These values can be determined experimentally. For the convenience of the further calculations, we also normalize K_p and K_d into the ranges $[0, 1]$ by the following linear transformation:

$$K'_p = (K_p - K_{p.\min})/(K_{p.\max} - K_{p.\min}),$$
$$K'_d = (K_d - K_{d.\min})/(K_{d.\max} - K_{d.\min}).$$

The integral gain, K_i, is obtained by the following equation [7].

$$K_i = K_p^2/(\alpha K_d).$$

After all, our goal is the determination of the parameters K'_p, K'_d, and α. To do this, we use a set of fuzzy rules of the form

$$IF\ e(k)\ is\ A_i\ and\ \Delta e(k)\ is\ B_i,$$
$$THEN\ K'_p\ is\ C_i,\ K'_d\ is\ D_i,\ and\ \alpha\ is\ \alpha_i$$
$$for\ i = 1, 2, \cdots, m. \tag{1}$$

A_i, B_i, C_i, and D_i are fuzzy sets on the corresponding supporting sets and α is a constant.

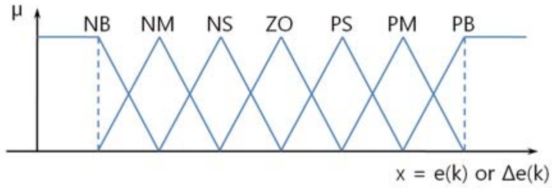

Fig. 6 Membership function for $e(k)$ or $\Delta e(k)$.

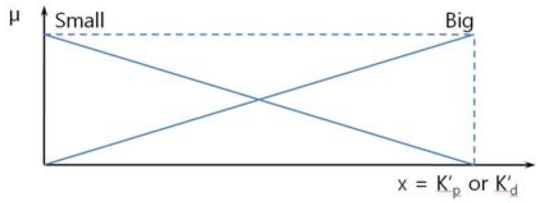

Fig. 7 Membership function for K'_p or K'_d.

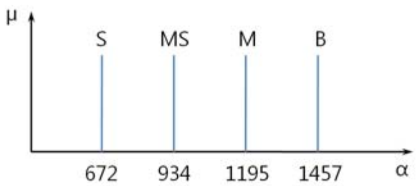

Fig. 8 Membership function for α.

Figs. 6 $\sim$ 8 show the membership functions of $e(k)$ or $\Delta e(k)$, K'_p or K'_d, and α, respectively. To calculate K'_p, K'_d, and α, we use the fuzzy rule as Table 1 $\sim$ 3 that is extracted from a typical curve of the desired time response. Consequently, we can determine values of K'_p,

Table 1 Fuzzy rule for K'_p

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
$e(k)$	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 2 Fuzzy rule for K'_d

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
$e(k)$	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

Table 3 Fuzzy rule for α

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
	NB	S	S	S	S	S	S	S
	NM	MS	MS	S	S	S	MS	MS
	NS	M	MS	MS	S	MS	MS	M
$e(k)$	ZO	B	M	MS	MS	MS	M	B
	PS	M	MS	MS	S	MS	MS	M
	PM	MS	MS	S	S	S	MS	MS
	PB	S	S	S	S	S	S	S

K'_d, and α by the following defuzzification.

$$K'_p = \sum_{i=1}^{m} \mu_i K'_{p.i},$$
$$K'_d = \sum_{i=1}^{m} \mu_i K'_{d.i},$$
$$\alpha = \sum_{i=1}^{m} \mu_i \alpha_i.$$

Here, μ_i is the membership value of the i^{th} rule in (1). $K'_{p.i}$ is the value of K'_p corresponding to the grade μ_i for the i^{th} rule (see Fig. 9). $K'_{d.i}$ is also obtained in the same way. In brief, the fuzzy output is obtained by using a singleton fuzzifier, a product inference engine, and a center-average defuzzifier. Further details for this method can be found in [7].

The parameters inserted into the actual Algorithm 3 are calculated from the following equations.

$$K_p = (K_{p.\max} - K_{p.\min})K'_p + K_{p.\min},$$
$$K_d = (K_{d.\max} - K_{d.\min})K'_d + K_{d.\min},$$
$$K_i = K_p^2/(\alpha K_d).$$

5. EXPERIMENT

We compare three control algorithms (Algorithm 1, 2, and 3) using the new mobile robot. Figs. 10 $\sim$ 21 show

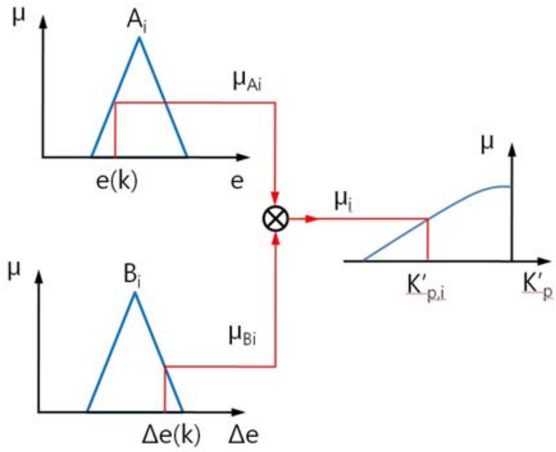

Fig. 9 Product inference engine of fuzzy rule.

the results of experiments when the mobile robot is controlled to move along the X, Y, and θ directions. The blue-dashed line represents the desired velocity profile, and the red-solid line the real velocity profile calculated from the measured encoder data. In the aspect of the RMS velocity error, Algorithm 3 has better performance than Algorithm 1 and 2.

The parameter's values of Algorithm 3, $K_{p.\min}$, $K_{p.\max}$, $K_{d.\min}$, $K_{d.\max}$, $K_{i.\min}$, and $K_{i.\max}$, are 5000, 6500, 100, 120, 290, and 310, respectively. In this case, the values of S, MS, M, and B in the membership function for α are 672, 934, 1195, and 1457. The minimum and maximum of the center values in the membership functions for $\Delta e(k)$ and $e(k)$ are -0.00798, 0.00798, -0.00498, and 0.00498, respectively. The gaps between the center values of each membership function are 0.00266 and 0.00166. Fig. 13, 17, and 21 show that Algorithm 3 changes the parameters to find the optimal control inputs of the mobile robot.

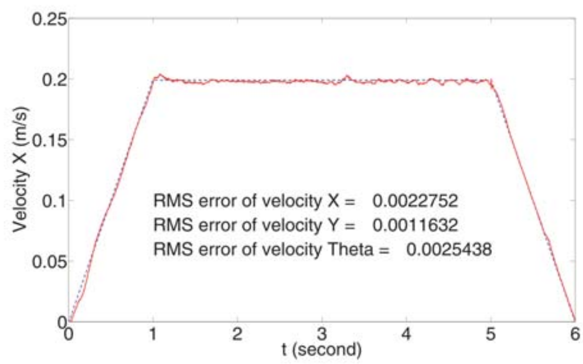

Fig. 10 Result of Algorithm 1 (X-direction).

Table 4 describes the average values of RMS velocity error after ten times experiments along each direction. This also says Algorithm 3 carries out finer control of the mobile robot than Algorithm 1 and 2.

6. CONCLUSION

In this paper, we introduced the new design of the omni-directional mobile robot with Mecanum wheel to

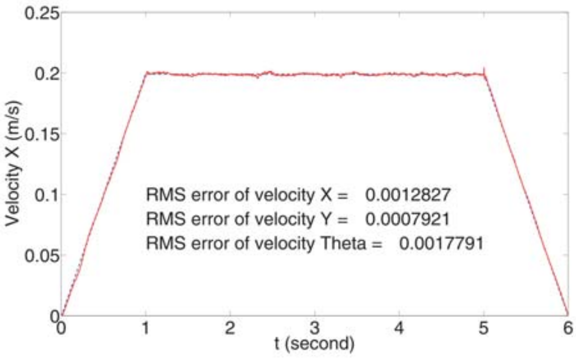

Fig. 11 Result of Algorithm 2 (X-direction).

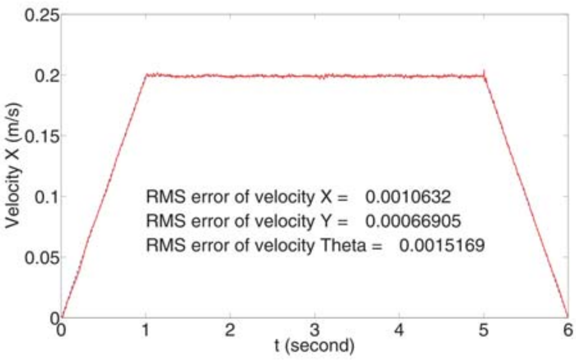

Fig. 12 Result of Algorithm 3 (X-direction).

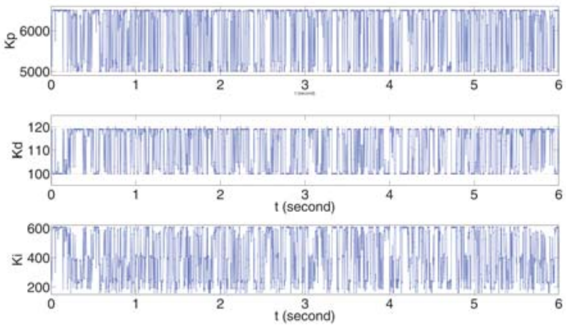

Fig. 13 Parameters of Algorithm 3 (X-direction).

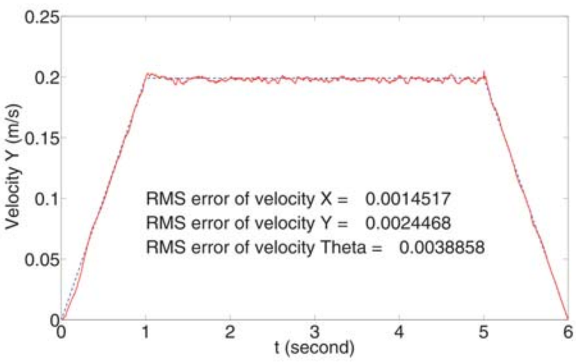

Fig. 14 Result of Algorithm 1 (Y-direction).

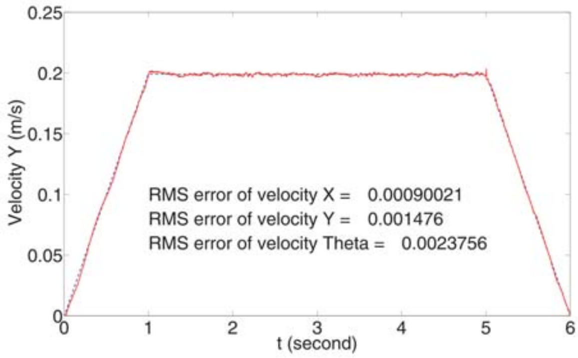

Fig. 15 Result of Algorithm 2 (Y-direction).

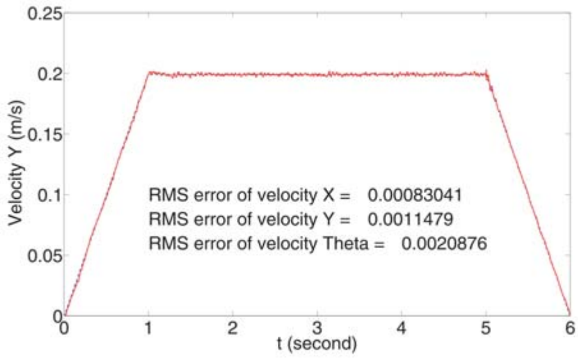

Fig. 16 Result of Algorithm 3 (Y-direction).

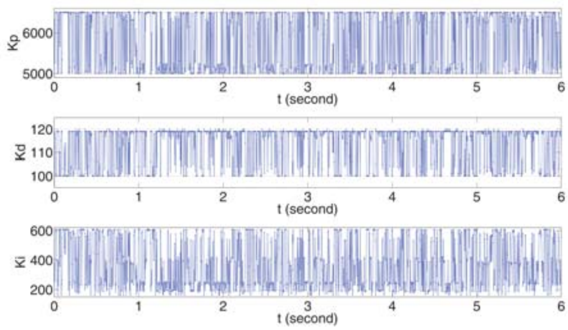

Fig. 17 Parameters of Algorithm 3 (Y-direction).

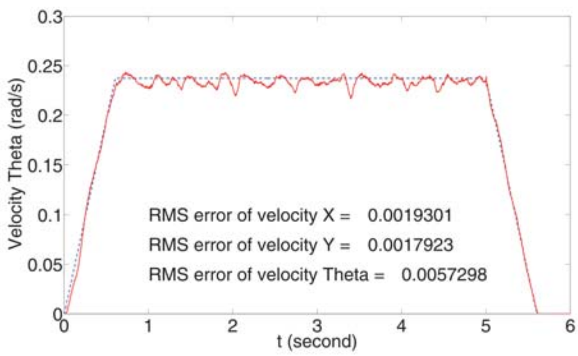

Fig. 18 Result of Algorithm 1 (θ-direction).

overcome the weak points of the previous robot. We implemented and tested the PID gain scheduling algorithm using the fuzzy system because it is hard to find the optimal values of the parameters, K_p, K_d, and K_i, in the conventional PID controller with the fixed gains. This algorithm (Algorithm 3) shows better performances for the mobile robot's movement.

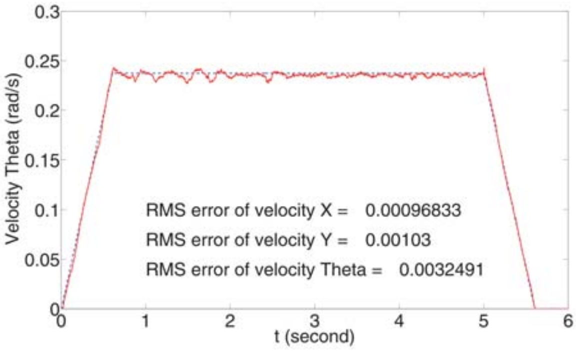

Fig. 19 Result of Algorithm 2 (θ-direction).

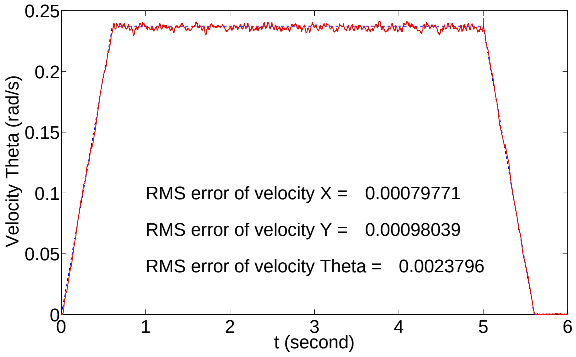

Fig. 20 Result of Algorithm 3 (θ-direction).

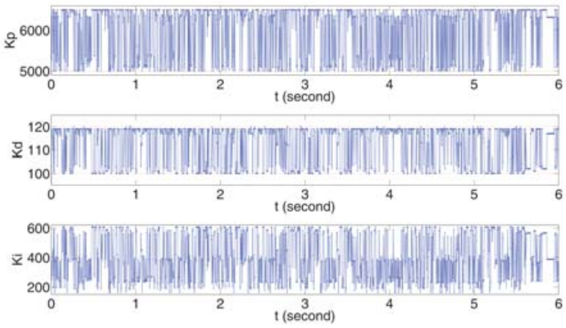

Fig. 21 Parameters of Algorithm 3 (θ-direction).

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Table 4 Average RMS velocity errors of 3 algorithms along 3 directions

		$RMSE_X$	$RMSE_Y$	$RMSE_\theta$
X	AL1	0.002145	0.001111	0.002676
	AL2	0.001269	0.000757	0.001831
	AL3	0.001034	0.000751	0.001744
Y	AL1	0.001504	0.002694	0.003749
	AL2	0.000916	0.001514	0.002737
	AL3	0.000902	0.001221	0.002609
θ	AL1	0.001607	0.001659	0.005783
	AL2	0.001002	0.001037	0.003388
	AL3	0.000903	0.000975	0.002509