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# An Efficient Approach for Line-Following Automated Guided Vehicles Based on Fuzzy Inference Mechanism

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**Abstract—Recently, there has been increasing attention paid to AGV (Automated Guided Vehicle) in factories and warehouses to enhance the level of automation. In order to improve productivity, it is necessary to increase the efficiency of the AGV, including working speed and accuracy. This study presents a fuzzy-PID controller for improving the efficiency of a line-following AGV. A line-following AGV suffers from tracking errors, especially on curved paths, which causes a delay in the lap time. The fuzzy-PID controller in this study mimics the principle of human vehicle control as the situation-aware speed adjustment on curved paths. Consequently, it is possible to reduce the tracking error of AGV and improve its speed. Experimental results show that the Fuzzy-PID controller outperforms the PID controller in both accuracy and speed, especially the lap time of a line-following AGV is enhanced up to 28.6% with the proposed fuzzy-PID controller compared to that with the PID controller only.**

***Keywords: Fuzzy-PID; Kinematic model; Line-following AGV; Line Detection***

## I. INTRODUCTION

A line-following AGV (Automated Guided Vehicle) is a kind of mobile robot that follows pre-planned routes. There has been much research about the advanced AMR (Autonomous Mobile Robot) that is capable of autonomous navigation in an unknown environment. The AMR demands expensive sensors such as LIDARs (Light Detection and Ranging) or TOF (Time of Flight) cameras for environment measurement. On the contrary, it is possible to exclude the expensive sensors from a line-following AGV because it tracks the pre-planned lines placed on the ground. The line-following AGVs are still common in the industry because of their reliability and efficiency.

With its popularity and efficiency, the PID (Proportional Integral Derivative) controller has been widely applied to line-following AGV studies [1-5]. In addition, control methods such as MSE controller (mean-square error controller) [6], visual controller [7], fuzzy controller [8-11], neural network [12], rotary controller [13], sliding mode controller [14, 15] and adaptive controller [16, 17] have also been used for AGV navigation. Surveys on the controller approach for AGV are available in [18, 19].

The above control methods all have their advantages and disadvantages, and none of the control methods has shown absolute superiority. On the other hand, the fuzzy logic algorithm has the advantage of being able to mimic human knowledge and experience on the control subject without the exact model parameters. Recent studies have mentioned the use of the fuzzy logic algorithm to change the gains of PID controllers [20-27]. In addition, the application of a fuzzy-PI controller to overcome the sliding phenomenon in omnidirectional AGV [28] or the parallel use of fuzzy and PID control to increase the efficiency of the control process has been proposed [29, 30]. However, with the ways of combining fuzzy logic with the PID controller mentioned above, the gain turning problem of the PID controller has not been overcome. When changing the model or changing the speed, the gain parameters need to be turned again. This is a huge limitation for the scalability of the AGV.

The fuzzy logic algorithm [31, 32] plays an important role in the navigation of a mobile robot beyond simply changing the gains of PID control. With the IF-THEN mechanism of its operation, the fuzzy logic algorithm allows the encoding of human knowledge of the environment into values that a mobile robot can understand. Thus, the quality of fuzzy controllers greatly depends on the experts. This method has the advantage of excluding the exact parameters of the environmental model in the control process. With today's complex robotic systems, the model parameters are not easy to find. Therefore, a fuzzy controller is increasingly more effective and widely applied. The controllability and the stability of the fuzzy controllers have also been researched and evaluated in [33, 34].

This study focuses on the problem of increasing the working efficiency of AGV. Specifically, in order to increase productivity, the AGV's operating speed needs to be further improved and, at the same time still, to ensure the control requirements. With the serial combination of the fuzzy logic controller and the PID controller, it is possible to take advantage of the two controllers by modularizing the overall control process. In addition, a large problem with PID controllers is that when you want the control to work well, it takes a lot of time to adjust the parameters of the system. However, with the Fuzzy-PID control proposed above, it is unnecessary to adjust and change the parameters of the PID controller, which makes AGV scalability and tuning simpler.

The process of the fuzzy-PID controller in this study is divided into two stages. The fuzzy controller first determines the speed of a line-following AGV according to the measurement of the ground lines. Next, the PID controller will ensure that the wheel motors work exactly as requested by the fuzzy controller. Because fuzzy logic plays a role in decision making, operators can encode the operational requirements and the most detailed environmental information of AGV. With its proven stability, the PID controller will ensure the demand from the fuzzy controller is met. Thus, the advantages of both controllers are taken in the proposed fuzzy-PID control.

The rest of the paper is presented in the following order. Modeling problems are presented in Section II. In Section III, the design and structure of a fuzzy logic algorithm and a PID controller are clarified. Experimental model parameters, experimental results, and a comparison of the results are given in Section IV. In section V, conclusions are drawn.

## II. AGV SYSTEM

An AGV in this study is a mobile robot with two wheels. To follow a guideline on the ground, a photo-graphic camera is mounted on the AGV.

### A. Kinematic Control

With the kinematic parameters of the AGV in Fig. 1, the linear velocity, $v$, and the angular velocity, $\omega$, of the AGV are presented as follows:

$$\begin{cases} v = \dfrac{v_r + v_l}{2} \\ \omega = \dfrac{2(v_r - v_l)}{L} \end{cases} \tag{1}$$

where $v_r$ and $v_l$ represent the linear speeds of the right and the left wheels, respectively, and $L$ denotes the distance between the two wheels.

To achieve line-following control, the desired values, $(v_d, \omega_d)$, of the AGV should be given as (2):

$$\begin{cases} v_d = \dfrac{p_e}{T} \\ \omega_d = \dfrac{\theta_e}{T} \end{cases} \tag{2}$$

where $p_e$ and $\theta_e$ represent the deviations of the position, and the rotation angle between the present and the desired states, respectively, and $T$ is the time required for the AGV to travel a distance $p_e$.

From (1) and (2), the command values of the angular velocities to the controllers of the left and the right wheel motors are given as follows:

$$\begin{cases} \omega_{rd} = \dfrac{1}{r}\left(v_d + \dfrac{L}{4} \cdot \omega_d\right) = \dfrac{1}{T \cdot r} \cdot \left(p_e + \dfrac{L}{4} \cdot \theta_e\right) \\ \omega_{ld} = \dfrac{1}{r}\left(v_d - \dfrac{L}{4} \cdot \omega_d\right) = \dfrac{1}{T \cdot r} \cdot \left(p_e - \dfrac{L}{4} \cdot \theta_e\right) \end{cases} \tag{3}$$

where $r$ represent the radius of the wheel.

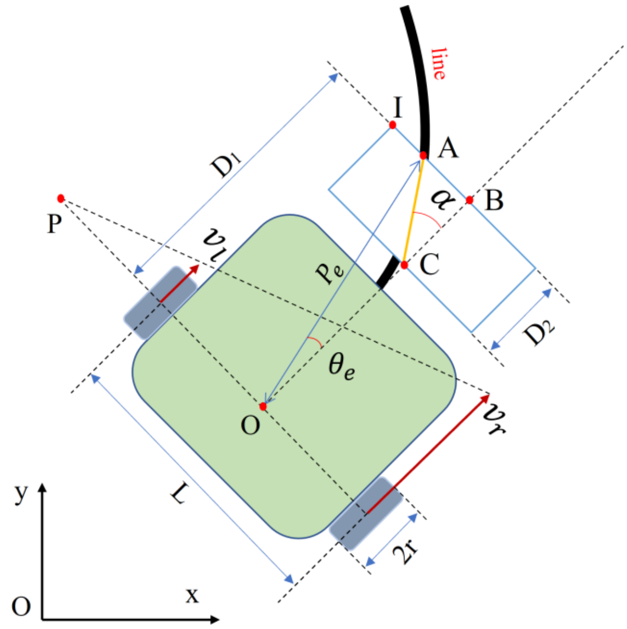



Fig. 1. AGV parameters.

### B. Line Detection by Imaging Camera

In this study, an imaging camera is used to detect the line on the ground. In the image from the camera represented by a blue box in Fig. 1, the deviation angle, $\alpha$, can be found by the following equation.

$$\alpha = tan^{-1}\left(\frac{\overline{IA} - \overline{IB}}{\overline{BC}}\right) \tag{4}$$

where $\overline{IA}$ and $\overline{IB}$ denote the lengths of a line between the points $I$ and $A$, and a line between the points $I$ and $B$. From the deviation angle, the following (5) is obtained:

$$\overline{IA} - \overline{IB} = \overline{BC} \cdot tan(\alpha) = D_2 \cdot tan(\alpha) \tag{5}$$

Thus, the deflection angle, $\theta_e$, is given by

$$\theta_e = tan^{-1}\left(\frac{\overline{IA} - \overline{IB}}{D_1}\right) = tan^{-1}\left(\frac{D_2 \cdot tan(\alpha)}{D_1}\right) \tag{6}$$

To ensure that the AGV can move along the line during operation, the ground line should always be in the area that the camera can measure. From the image size, the range of $\alpha$ is given by (7).

$$\begin{cases} \alpha_{min} = tan^{-1}\left(\dfrac{\overline{IA}_{min} - \overline{IB}}{\overline{BC}}\right) \\ \alpha_{max} = tan^{-1}\left(\dfrac{\overline{IA}_{max} - \overline{IB}}{\overline{BC}}\right) \end{cases} \tag{7}$$

Thus, the permissible upper and lower limits of $\theta_e$ are computed as (8).

$$\begin{cases} \alpha_{min} = tan^{-1}\left(\dfrac{\overline{IA}_{min} - \overline{IB}}{\overline{BC}}\right) \\ \alpha_{max} = tan^{-1}\left(\dfrac{\overline{IA}_{max} - \overline{IB}}{\overline{BC}}\right) \end{cases} \quad (8)$$

where the distances $D_1$ and $D_2$ are given by the camera setup of the AGV.

## III. LINE-FOLLOWING CONTROL

### A. PID Control

PID control has been widely used in industry with proven performance. In [4], Gomes et al. applied the PID control algorithm for their line-following mobile robot. The input parameters of the line-following AGV include $p_e$ and $\theta_e$ as shown in (3). However, the parameter $p_e$ is regarded as constant in [4] to implement the PID controller. The value of $p_e$ is determined by experiment.

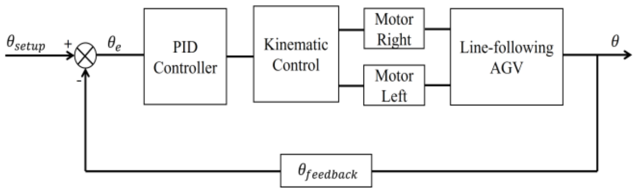



Fig. 2. PID control for a line-following mobile robot.

Fig. 2 shows the PID control structure for the line-following mobile robot. When input $\theta_e$ is specified, the PID controller will give a control signal to ensure that the mobile robot can follow the guidelines on the ground. The kinematic control then calculates the velocity values for the wheels. In the next stage, the deflection angle, $\theta_e$, will be reflected and compared with the set value.

### B. Fuzzy-PID Controller

#### 1) Structure of fuzzy-PID controller

In order to improve the productivity of the AGV, it is necessary to simultaneously increase the line-following speed and secure the control safety of the AGV. Based on these requirements, a fuzzy-PID control scheme is proposed in this study. The fuzzy-PID controller mimics the principle of human vehicle control as the situation-aware speed adjustment on curved paths. In essence, the role of fuzzy logic is to make decisions to increase or decrease the speed of the wheels under specific environmental conditions, and the PID controller will ensure accurate and stable implementation of those decisions. The proposed control structure is represented in Fig. 3.

As shown in Fig. 3, the proposed fuzzy-PID control operates in two stages. After the deviation angle, $\alpha$, and the deflection angle, $\theta_e$, are obtained, the fuzzy logic block determines the commands of the angular velocities of the two wheels to ensure that the AGV correctly follows the guidelines on the ground. Once the wheel velocity commands are determined, the PID controller will ensure that the wheel motors properly execute the velocity commands given by the fuzzy controller.

The main advantage of the proposed fuzzy-PID control is to customize the AGV's speed according to the environmental situation based on the operating principle explained above. Depending on the environment, the proposed controller can operate in different modes such as acceleration, deceleration, or reaction to external events by mimicking human operators. Therefore, the AGV has the necessary intelligence about the surrounding environment by approximating human knowledge and experience using fuzzy rules.

#### 2) Fuzzy controller design

The fuzzy logic controller is designed according to the human experience: driving a car at high speeds on straight sections of the road and slowing down when the car approaches a curved section not to be thrown off the road. Thus, the linear speed and the steering speed depend on the curvature of the road. By applying these principles to AGV, the desired values of two main velocity components, $v$, and $\omega$, can be determined. That is, if $\theta_e$ is small, then $v_d$ increases and $\omega_d$ decreases. Conversely, when $\theta_e$ is large, then $v_d$ decreases and $\omega_d$ increases. With the above arguments, the fuzzy controller structure is presented in Fig. 4.

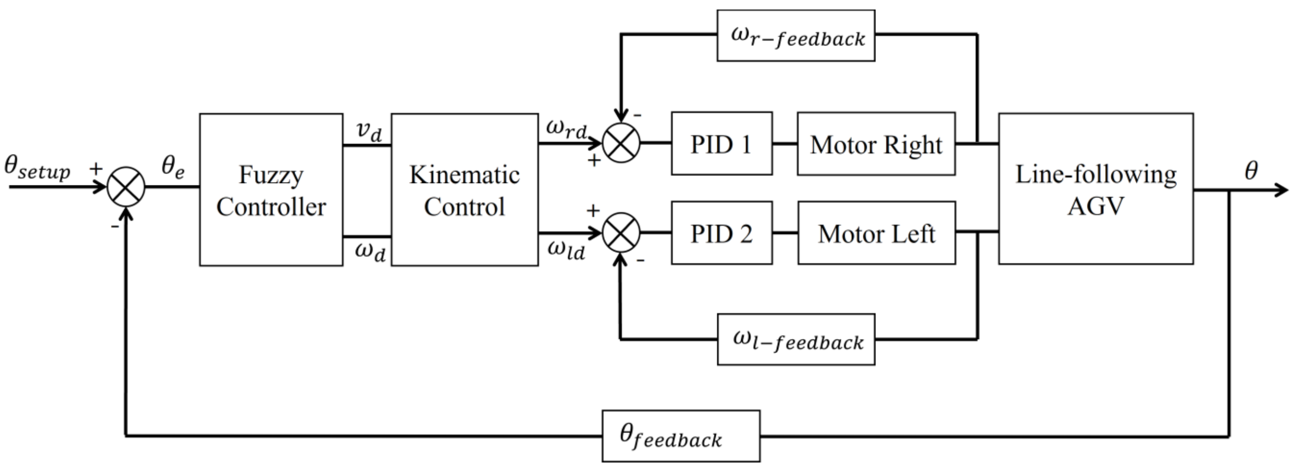



Fig. 3. Block diagram of a fuzzy-PID controller.

TABLE I. FUZZY RULES OF THE PROPOSED CONTROLLER.

| | | Input $\theta_e$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | ZE | PS | PM | PB |
| **Output** | $v_d$ | ZE | PS | PM | PB | PM | PS | ZE |
| | $\omega_d$ | NB | NM | NS | ZE | PS | PM | PB |

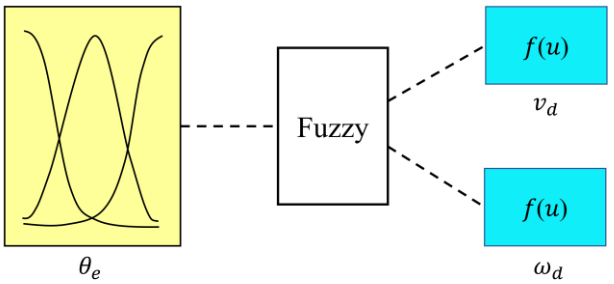



Fig. 4. The structure of the fuzzy controller.

In the structure shown in Fig. 4, the input $\theta_e$ is fuzzified by 7 fuzzy sets, {NB, NM, NS, ZE, PS, PM, PB}, and the outputs, $v_d$ and $\omega_d$, are fuzzified by 7 fuzzy sets and 4 fuzzy sets, respectively, as {NB, NM, NS, ZE, PS, PM, PB} and {ZE, PS, PM, PB}, as shown in Fig. 5 through Fig. 7. The linguistics NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big) represent the corresponding fuzzy sets. The domain of the input and output variables of the fuzzy controller is determined by experiment.

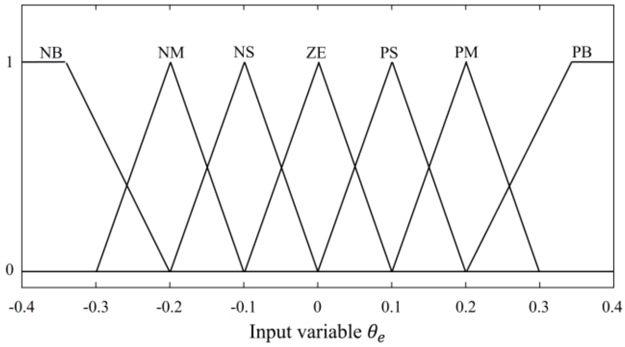



Fig. 5. Fuzzy sets for $\theta_e$.

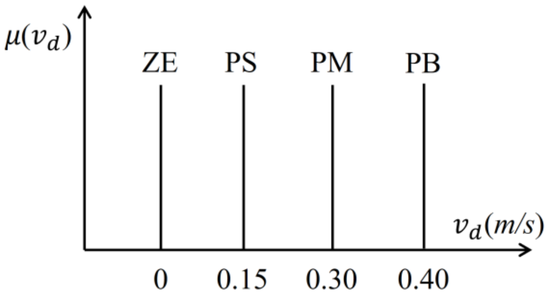



Fig. 6 (a). Fuzzy sets for $v_d$.

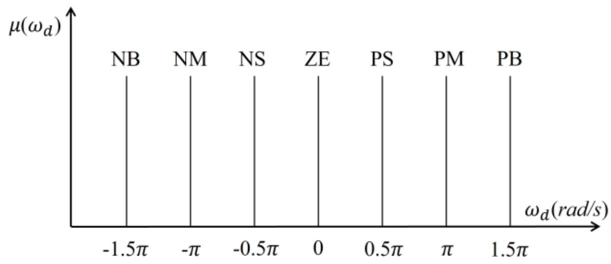



Fig. 6 (b). Fuzzy sets for $\omega_d$.

The fuzzy rules representing the basic human experience for AGV control are described in Table I.

## IV. RESULTS OF EXPERIMENT

### A. AGV System

In order to verify the proposed fuzzy-PID controller, experiments were conducted using the AGV [35] with the guideline on the ground, as shown in Fig. 7 and 8. Specifications of the AGV are summarized in Table II.

TABLE II. SPECIFICATIONS OF AGV [35].

| Specifications | Values |
|---|---|
| Weight | 8.5 kg |
| Speed | 5.2 km/h |
| Radius of wheel | 7.5 cm |
| Distance between two wheels | 28.90 cm |

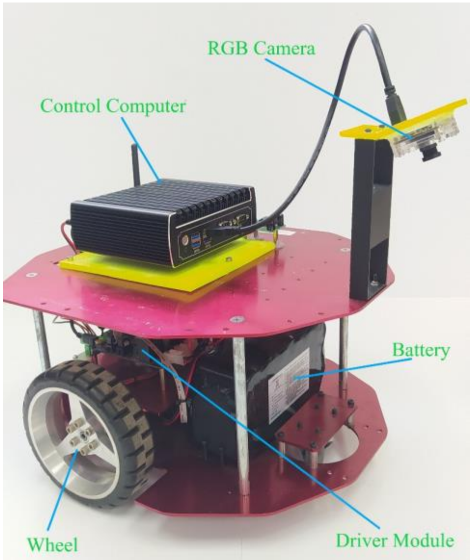



Fig. 7. AGV.

### B. Fuzzy Control for Experiment

In this study, the image obtained from the camera is $320 \times 240$ pixels in size. From (7), the limits for $\alpha$ are expressed as follows.

$$\begin{cases} \alpha_{min} = tan^{-1}\left(\frac{0-160}{240}\right) = -0.588\ rad \\ \alpha_{max} = tan^{-1}\left(\frac{320-160}{240}\right) = 0.588\ rad \end{cases} \tag{9}$$

In addition, the values of $D_1$ and $D_2$ are $61cm$ and $34cm$, respectively. By substituting the values into (8), the permissible range of $\theta_e$ is given by

$$\begin{cases} \theta_{emin} = tan^{-1}\left(\frac{34 \cdot tan(-0.588)}{61}\right) = -0.356\ rad \\ \theta_{emax} = tan^{-1}\left(\frac{34 \cdot tan(0.588)}{61}\right) = 0.356\ rad \end{cases} \tag{10}$$

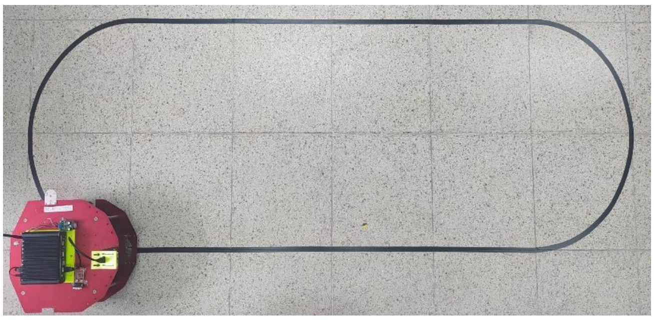
#### 1) Input fuzzy sets

From (10), the domain of fuzzy input sets in Fig. 5 is determined as NB = -0.356 *rad* and PB = 0.356 *rad* for the fuzzy controller. Because the maximum and minimum range of $\theta_e$ is symmetric, the value for the linguistic variable ZE is chosen as 0 *rad*. The linguistic variables NS and NM will range from -0.356 *rad* to 0 *rad*. The exact values of NS and NM are obtained empirically during the experiments. Similarly, the values of PS and PM will range from 0 *rad* to 0.356 *rad*, respectively; their exact values were also found experimentally.

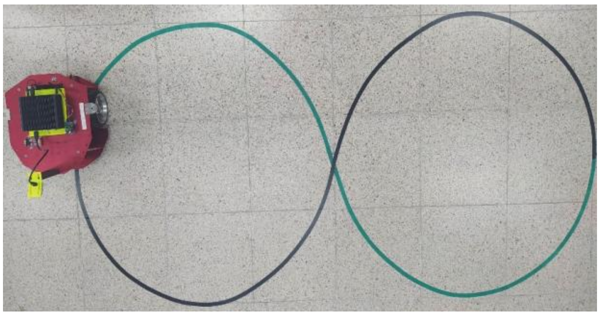
#### 2) Output fuzzy sets

The linear velocity, $v_d$, is assigned the linguistic variables ZE, PS, PM, and PB. Because the line-following AGV moves forward or stands still and does not move backward, the value of ZE is chosen as 0 *m/s*. The value of PB is chosen as 0.4 *m/s*, which is the maximum stable linear velocity of the AGV in a straight line. The values of PS and PM are chosen in the range, and they were adjusted during the experiments. The values selected in this study are shown in Fig. 6(a).

The values of $\omega_d$ were determined in the same method as that of $\theta_e$ as shown in Fig. 6(b).



(a) The oval guideline.



(b) The figure-8 guideline.

Fig. 8. Guideline on the ground.

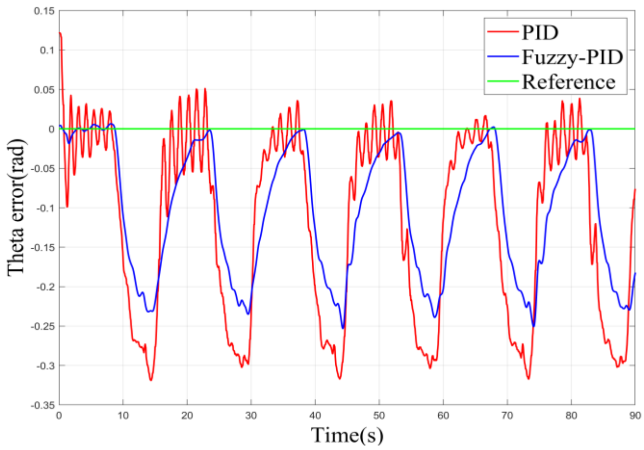
### C. Result of Experiment

In order to verify the proposed fuzzy-PID control for a line-following AGV, experiments were conducted on two different trajectories, as shown in Fig. 8.

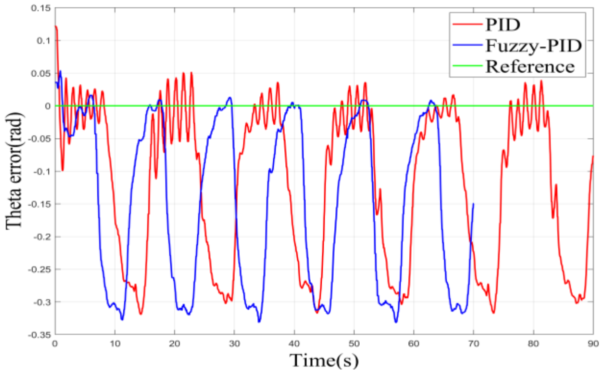
#### 1) The oval guideline

The length of a closed-loop guideline is 5.712*m*. The AGV tracks the loop of guidelines three times for a total distance of 17.136*m*.

By comparing the performance of the fuzzy-PID controller with the PID controller, the effectiveness of the proposed controller is shown in Fig. 9. Firstly, considering the quality of rotation control, the fuzzy-PID controller gives a much smoother graph than the PID controller, as shown in Fig. 9a where the path command with the same lap period is used for both controllers. The maximum $\theta_e$ is 0.251 *rad* when the AGV is controlled by the proposed fuzzy-PID controller, while it is 0.319 *rad* when the AGV is controlled by the PID controller. It is noted that $\theta_e$ can be reduced by slowing down the speed of AGV. The experimental results in Fig. 9(a) are obtained in the same average speed levels of the AGV with the fuzzy-PID controller and the PID controller only. With the same level of $\theta_e$ as shown in Fig. 9(b), the fuzzy-PID controller took 70 *sec* to complete the navigation, while the PID control took 90 *sec*. The average speed of the AGV using the fuzzy-PID controller is 0.2448 *m/s*, while it is 0.1904 *m/s* using only the PID controller. The speed increase of the fuzzy-PID controller over the PID controller is 28.57 percent.




(a) The same lap period: same average speed level.



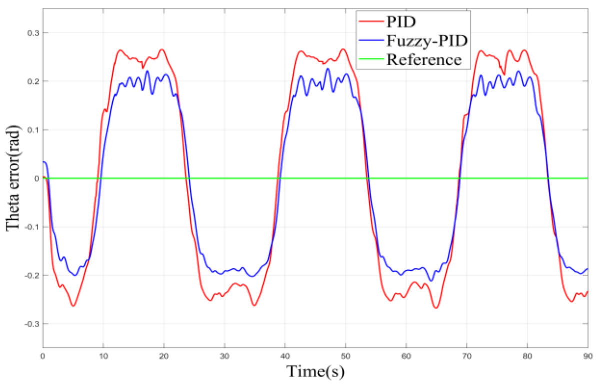

(b) The same level of theta error.

Fig. 9. Results with PID control and fuzzy-PID control on the oval guideline.

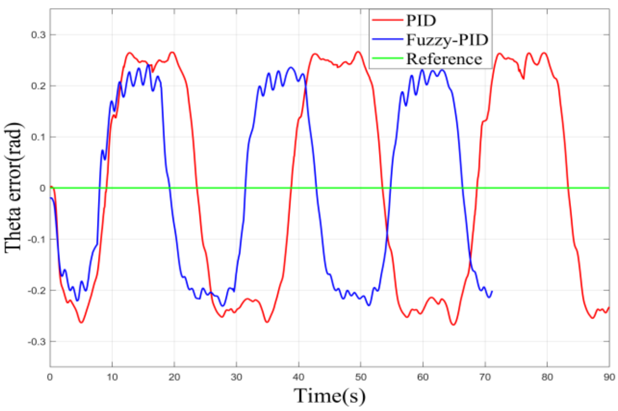
### 2) The figure-8 guideline

With the trajectory shown in Fig. 8(b), the length of a closed loop is 7.54*m*. To increase the test time, the AGV completed three laps for a total distance of 22.62*m*.

The results from Fig. 10 once again confirm the effectiveness of the fuzzy-PID controller. As the graph in Fig. 10(a) shows, the maximum value of $\theta_e$ is 0.274 *rad* when using PID control. As for fuzzy-PID control, it's only 0.219 *rad*. The AGV was driven along the same path, and the equivalent $\theta_e$ value for the two controls, and the results are shown in Fig. 10(b). The fuzzy-PID controller needed 72 *sec* to complete the path, while the PID controller needed 90 *sec*.




(a) The same lap period: same average speed level.




(b) The same level of theta error.

Fig. 10. Results with PID and Fuzzy-PID controls on the figure-8 guideline.

### 3) Result in comparisons

The experimental results of the PID controller and the fuzzy-PID controller in this study are summarized in Table III. For the same lap period, the deflection angle, $\theta_e$, is compared between the two control methods. For the same level of $\theta_e$, the velocity of a line-following AGV is compared.

TABLE III. EXPERIMENTAL COMPARISON RESULTS.

| | *The oval guideline* | | *The figure-8 guideline* | |
|---|---|---|---|---|
| | PID | Fuzzy-PID | PID | Fuzzy-PID |
| Distance (*m*) | 17.136 | 17.136 | 22.62 | 22.62 |
| Time (*s*) | 90 | 70 | 90 | 72 |
| Velocity (*m/s*) | 0.190 | 0.2448 | 0.2513 | 0.3142 |
| $\theta_e$-max (*rad*) | 0.319 | 0.251 | 0.274 | 0.219 |
| $\theta_{emax}$ (*rad*) | 0.356 | 0.356 | 0.356 | 0.356 |
| $\theta_e$-max (%) | 89.61 | 70.51 | 79.97 | 61.52 |

## V. CONCLUSIONS

In this paper, a fuzzy-PID control method has been presented for a line-following AGV by combining the advantages of two controllers. The velocity of the AGV is determined via fuzzy logic. It can be fast or slow, depending on the curvature of the path on the ground. Then, the PID controller will ensure that the motor executes the velocity required by the fuzzy control. Experimental results show the effectiveness of the proposed control method in increasing the AGV's speed on a curved path (Fig. 9(b) and Fig. 10(b)) and, at the same time, ensuring its stability (Fig. 9(a) and Fig. 10(a)). In addition, the Fuzzy-PID controller outperforms the PID controller in both accuracy and speed, especially the lap time of a line-following AGV is enhanced up to 28.6% with the proposed fuzzy-PID controller compared to that with the PID controller only. The fuzzy controller can also help the AGV to know how to react to problems during operation. With the application of the fuzzy-PID control method for AGV, the working efficiency of AGV will be significantly increased, thereby improving productivity of the AGV.

In the future, the influence of factors such as friction force and inertia force will be studied and added to the control model. In addition, fuzzy logic optimization methods will be studied and tested.

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