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The Effectiveness of LEGO Mindstorms NXT in Following Complicated Path Using Improved Fuzzy-PID Controller

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Abstract— **Line follower robots are monotype mobile robot having the ability to follow a line very accurately. Though many researchers are studying regarding line follower robot but most of the concepts are concentrated on theoretical design. The performance of the conventional type of controller in controlling line follower robot is still being a popular topic to be discussed. The traditional controller cannot deal with uncertainty data such as the amount of light whether it is too high or too low light that received by the light sensor which leads to the inaccurate movement of the line follower robot. This research presents an application of improving fuzzy-PID controller method in controlling LEGO Mindstorms NXT while following the complicated path with more accurate and high velocity. LEGO Mindstorms NXT with single light sensor is used as a line follower robot to tracking the complicated black line drawn on the white surface. The investigation of existing method for line following application will help in identifying the best controller method of inspecting the pattern of line follower robot movement. At the end of the research, the movement of LEGO Mindstorms NXT robot is more accurate with high complexity of line by using improved fuzzy-PID controller. The improved fuzzy-PID controller also increases the velocity of the robot when tracking the complicated path.**

Keywords— Improved Fuzzy-PID, Complicated Path, LEGO Mindstorms NXT, Accurate, Velocity.

I. INTRODUCTION

Line following is one of the most practical application as it allow the robot to moving from one point to another to perform tasks as previous study [1]. The situations become worst when robots need to follow the complicated and small thickness of line such as thin sharp curve line. The existing methods to control line following robot is still being issue on how to improve the performance of line follower robot. The traditional algorithm for line follower robot movement is, it will turn left when there is no line detected by the sensor and it will turn right when the line is detected by the sensor. This algorithm is very slow and not accurate, wasting valuable time and battery power. Line follower robot algorithm using conventional PID is much better than the earlier algorithm but the robot still will be unsteady about the line. Mas Pratama et al. [2] stated that the disadvantages of PID control system is, if given light sensor value are increasingly sensitive the response will overshoot and undershoot. However, if the light sensor value is made less sensitive to the response, there will be a recovery process which takes longer. So will cause the movement of robots are increasingly chaotic and unstable. On other hand, Hagras [3] found that to design a robust controller which can provide copacetic performance in the face of skeptical and imprecision, fuzzy logic controller is credited with being an adequate methodology.

II. BACKGROUND STUDIES

A. *Comparison of Improved Fuzzy-PID and Non-Improved Fuzzy-PID*

In the before technology, they were many methods used to design and implement, and also different algorithms were used for line follower robot. The most common and popular line tracing methods are simple Boolean logic, PID controller, and fuzzy logic controller. Each line following controller technique has its own advantages and disadvantages. In this section, the proposed fuzzy-PID controller that is improved fuzzy-PID is compared with non-improved fuzzy-PID. In previous studies [2, 4, 5], the authors does not proven the fuzzy-PID controller that their introduced will improve the performance of the robot from aspect accuracy and velocity while following the complicated line following. Table I show the differences between the proposed fuzzy-PID which is called as an improved fuzzy-PID controller and the non-improved fuzzy-PID controller.

Table I. Differences of Proposed or Improved Fuzzy-PID Controller and Non-Improved Fuzzy-PID Controller

Type of Fuzzy-PID	**Differences**
Non-Improved Fuzzy-PID	Fuzzy logic serves to help determine the value parameter error and the previous error value changes (Derror) [2].
Non-Improved Fuzzy-PID	PID controller serves for steering purpose and fuzzy controller serves for efficient velocity of robot [4].
Improved Fuzzy-PID	PID controller serves to calculate the error which then will be used to evaluate the fuzzy rule.

III. IMPLEMENTATION OF IMPROVED FUZZY-PID

In accordance with the research title, the performance of line follower control system will be discussed in this research based hybrid between PID controller methods with fuzzy logic controller method. There will be two control methods that work together in the system. As on the basis of the theory of control systems, there is something which is the goal, the system needs to be controlled. The purpose of the form of the set point on line follower robot is a situation where the movement of the robot needs to remain accurate and faster.

The block diagram of the proposed or improved fuzzy-PID controller is shown in Fig 1. Fig 1 show the block diagram of the proposed fuzzy-PID controller. The first part of a program is a fuzzy logic controller while the second part of a program is a PID controller. After reading the light sensor value, ARM7 microcontroller executes the fuzzy logic controller and PID controller steps in sequence. After evaluation of sensor value in the fuzzy controller, this information will be sent to PID controller for next steps. The result of error will use for a fuzzy controller rule evaluation. The result of motor power for each control will be summed together which is used to control the movement of the LEGO Mindstorms NXT robot.

A. Fuzzy Logic Controller

In this section, the implementation of the fuzzy logic controller which is including the fuzzification process, rule base evaluation and defuzzification process is elaborated. The intensity of the reflected light is sensed to provide the function for tracing a path following. For simplified the system, one light sensor is utilized. In this research, MATLAB Fuzzy Logic Toolbox is used to avail in fuzzy logic controller design. The input and output membership functions are defined and are related with sets of rules. The outputs of fuzzy controllers control the power of two motors of the LEGO Mindstorms NXT robot. Fig 2 show the fuzzy logic inference system where there will be one input and to output in this research which the input is light intensity, and the output is left motor power and right motor power.

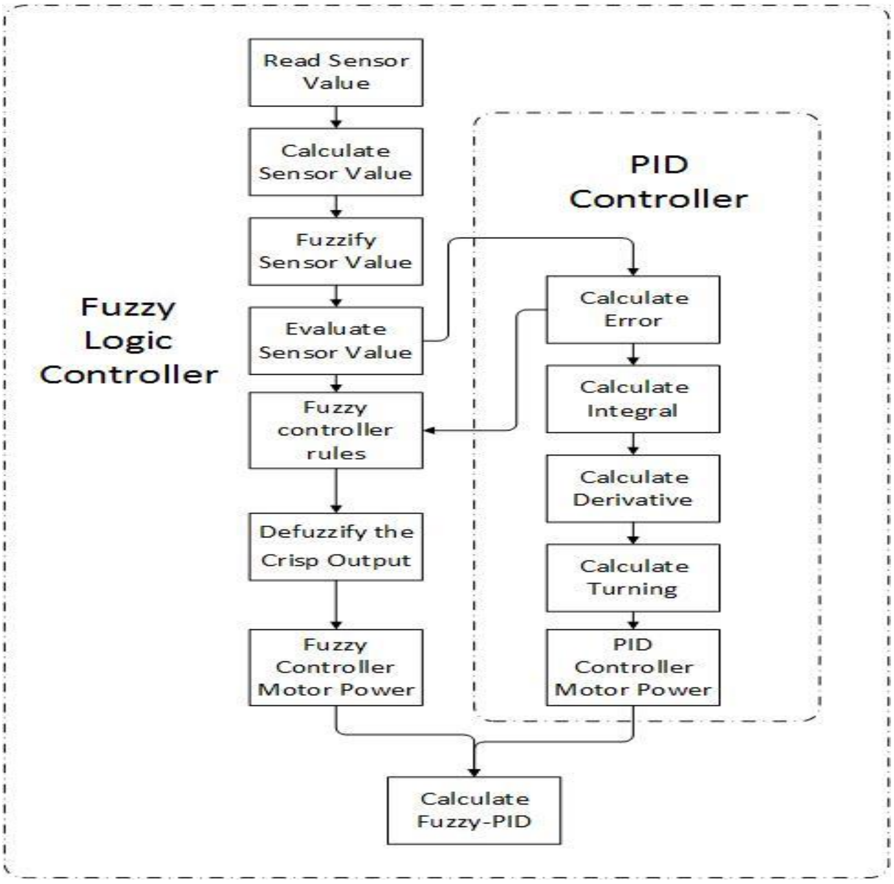

Fig 1. The Block Diagram of Improved Fuzzy-PID Controller

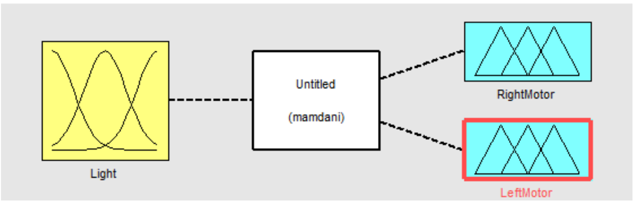

Fig 2. Fuzzy Logic Inference System

1) Fuzzification

The input and output membership functions are defined and are related to sets of rules [6, 7]. The input interface obtains the input values and maps them into suitable fuzzy sets represented by the membership functions. This process is also called the fuzzification [8]. To fuzzify the data deviate the central of dark line and white ground, the membership function of input intensity of light reflected is designed. Membership function shown in Fig 3 is used to fuzzify the value of the variable. The membership function considered here is a Trapezoidal type which input to a fuzzy logic controller that is the light is described by two fuzzy sets that are Black (L_b) where light is black and White (L_w) where light is white or bright. The range of light value being from 0 to 100 where the input of light is considered black if the range of the value is between 0 to 30. While the input of light is considered white if the range of the value is between 40 to 100. The description of these fuzzy sets is shown in Table II. Fig 3 show the membership functions for light which are described by the general expressions below:

$$L_b = \begin{cases} 30 - L_b, & 0 \leq L_b \leq 20 \\ L_b - 30, & 20 \leq L_b \leq 60 \end{cases} \quad (1)$$

$$L_w = \begin{cases} 60 - L_w, & 0 \leq L_w \leq 60 \\ L_w - 60, & 60 \leq L_w \leq 100 \end{cases} \quad (2)$$

Table II. Fuzzy Sets that Represent the Input

Fuzzy Set	Description
L_b	The sensor value when to detecting the black line
L_w	The sensor value when no black line is detected

In which L_b and L_w are the input of the light in which the subscripts 'b' represent black and the subscripts 'w' represent white.

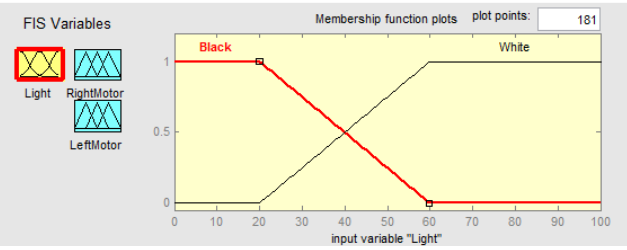

Fig 3. Input Intensity of Light Reflected Membership Function

The membership function for the aimed output of the right motor and left motor is shown in Fig 4 and Fig 5. The membership function is a triangular type which right motor (RM) and left motor (LM) speeds are described by two fuzzy sets that are Slow and Fast. The definition of these sets is shown in Table III.

Table III. Fuzzy Sets Defined for Output

Fuzzy Set	Description
Slow	Speed of left or right motor is low
Fast	Speed of left or right motor is high

The membership functions for Right Motor and Left Motor, as shown in Fig 4 and Fig 5, are described by the expressions:

$$Right\ Motor\ (rm_s) = -rm_s(2) \qquad 0 \leq rm_s \leq 100 \quad (3)$$

$$Right\ Motor\ (rm_f) = rm_f(2) \qquad 0 \leq rm_f \leq 100 \quad (4)$$

$$Left\ Motor\ (lm_s) = -lm_s(2) \qquad 0 \leq lm_s \leq 100 \quad (5)$$

$$Left\ Motor\ (lm_f) = lm_f(2) \qquad 0 \leq lm_f \leq 100 \quad (6)$$

In which rm are the motor power of the right motor and lm are the motor power of the left motor in which the subscripts 's' represent slow and the subscripts 'f' represent fast.

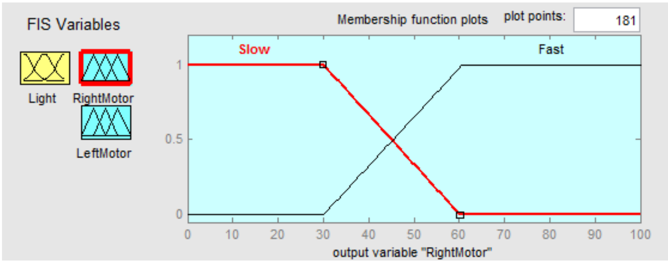

Fig 4. Right Motor Membership Function

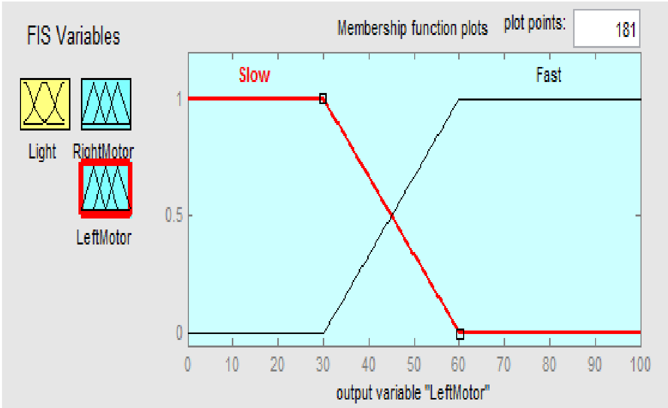

Fig 5. Left Motor Membership Function

2) Rule Base

There are only two rules for determining desired power to follow the pre-defined path whether the right or left motor is fast or slow depends on the value of light readings. In this research, the value of light reading is between our minimum and maximum light readings which are in the range between 0 to 100. The value of light is an error *(e)* that have been calculated in PID controller part where error value is calculated using the variable from the intensity light value. The light error is considered black if the range of the value is between zero to 30. While the light error is considered white if the range of the value is between 40 to 100. The value of the error will be used when the correction is set to the robot motors. The description of the fuzzy rules is as Table IV.

Table IV. Fuzzy Rules of Desired Power

$Light / \nabla Light$	Right Motor	Left Motor
Black	Slow	Fast
White	Fast	Slow

Because we can absorb and simplify rules into two rules, a curve line appears on the surface viewer with the graph of desired power and the light reflected intensity which is shown in Fig 6 and Fig 7.

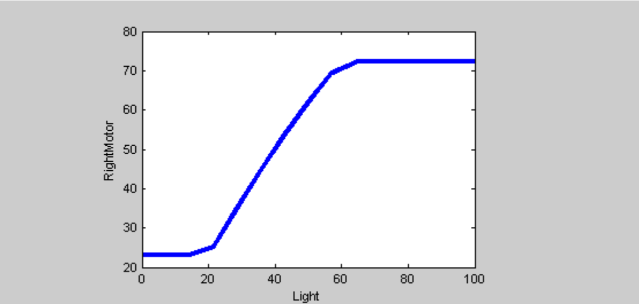

Fig 6. Graph of Light versus Right Motor

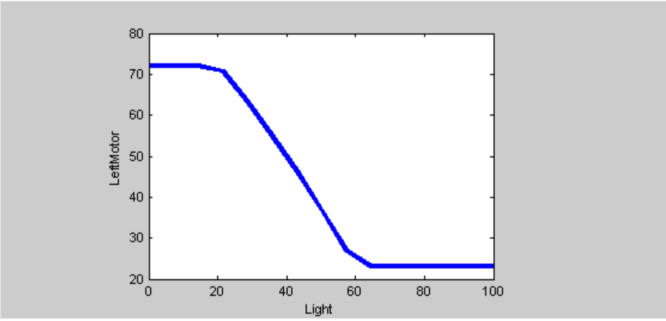

Fig 7. Graph of Light versus Left Motor

3) Defuzzification

If the values considered in the fuzzy sets are regarding degree variation then in the final output the fuzzy values should be converted into a crisp value by using any defuzzification method. Center of Area (COA) is the easiest and commonly defuzzification method. As inference with Matlab utility, Fig 8 is shown for rules viewer of the membership function. As shown above words of Fig 8, while we drag the vertical red-line of light membership function with the mouse in Matlab utility, we can get the output of the right motor and left motor. And the vertical red-line is the output of defuzzification with COA method, as shown with 29.1m^{-1} for right motor and 67.9 m^{-1} for left motor when the input of the light error that received from the PID controller is 24.3.

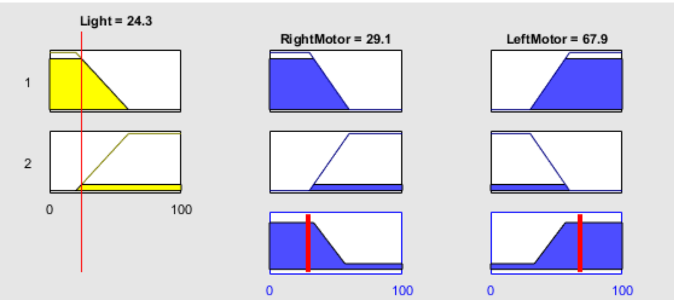

Fig 8. Rules Viewer for the Membership Function

B. PID Controller

1) Proportional

The value of light sensor reading from the fuzzy part is used by a proportional controller to calculate the error which then will be used to evaluate the fuzzy rule. The basic formula of a proportional controller is:

$$P_{out} = K_p e(t) \tag{7}$$

Where P is proportional, K_p is the proportional constant value, *e* (t) is the error value is always going to change. Different with the basis of the theory of PID, which the error value obtained from:

$$e\text{: error} = PV - SP \tag{8}$$

Where *SP* is Setpoint, *PV* is the Process Variable. If converted into the syntax of the program will be becomes:

Setpoint = 45
K_p = 1.5
error = *69.3 – 45 = 24.3*
P = K_p × error
P = 1.5 × 24.3 = 36.45

2) Integral

The basic formula of Integral controller is:

$$I_{out} = K_i \int_o^t e(t)\ dt \tag{9}$$

Where I was Integral, K_i is the integral constant value, *e* (t) is the value of the error, dt is the rate of change of time (second). The Integral controller cannot be used alone, so it must be coupled with a controller proportional. If converted into the syntax of the program will be becomes:

Setpoint = 45
serror = *69.3 – 45 = 24.3*
P = K_p × error
P = 1.5 × 24.3 = 36.45
I1 = error
I = I1 × K_i
I = 24.3 × 0.001 = 2.403
PI = P + I
PI = 36.45 + 2.403 = 38.853

3) Derivatives

The basic formula of the controller derivatives are:

$$D_{out} = K_d \frac{d}{dt} e(t) \tag{10}$$

Where D is derivatives, K_d is a constant value of derivatives, d*e* (t) is the rate of change of the error, dt is the rate of change of time (second). Likewise with Integral controller, derivatives controller also cannot be used alone, but also must be combined with proportional controller. If not, then the controller Derivatives will not be able to perform any action, because there is no change in the error. If converted into the syntax of the program will be becomes:

Setpoint = 45
error = *69.3 – 45 = 24.3*
P = K_p × error
P = 1.5 × 24.3 = 36.45

D1 = error – last_error
D1 = 69.5 – 69.3
D = D1 × K_d
D = 0.2 × 15 = 3
PD = P + D
PD = 36.45 + 3 = 39.45
So if all three controllers are combined, then the syntax of the program will be:
Setpoint = 45
error = *PV – SP*
P = K_p × error
P = 1.5 × 24.3 = 36.45
I1 = error
I = I1 × K_i
I = 24.3 × 0.001 = 2.403
D1 = error – last_error
D1 = 69.5 – 69.3
D = D1 × K_d
D = 0.2 × 15 = 3
last_error = error
PD = P + D
PD = 36.45 + 3 = 39.45
PID = PD + I
PID = 39.45 + 2.403 = 41.583

The proportional, integral and derivative outputs are used to calculate the value of turning point which if converted into syntax of the program will be:
Right Motor = Turning point – PID
Right Motor = 15 – 41.583 = 26.583 m^{-1}
Left Motor = Turning Point + PID
Left Motor = 15 + 41.583 = 56.583 m^{-1}

sThis value is after that will be used to calculate the motor power which is used to sum with the output of the Fuzzy Cripst output. The result of the sum will be used to control the motor power of LEGO Mindstorms NXT robot. It can be shown pieces program syntax summation and control the speed of rotation of the motor as follows:
Right Motor = Fuzzy Output + PID Output
Right Motor = 29.1 + 26.583 = 55.683 m^{-1}
Left Motor = Fuzzy Output + PID Output
Left Motor = 67.9 + 56.583 = 124.483 m^{-1}

IV. EXPERIMENTAL SETUP

A. *Lego Mindstorms NXT*

In this research, LEGO Mindstorms NXT which is equipped with the single light sensor and programmed with controller method as shown in Fig 9 is used to follow a pre-defined path. The control algorithms are programmed on the RobotC environment. The main component of the LEGO Mindstorms NXT kit is a brick computer called NXT Intelligent Brick. The NXT intelligent brick has two microcontrollers which is one of the microcontrollers is use for running the main applications and other one is for controlling the motors. Both microcontrollers are equipped with Flash memory so they will not lose the programs nor the firmware if one removes the batteries.

Fig 9. LEGO Mindstorms NXT

B. *Pre-Defined Path Following*

To validate the proposed control algorithm, a pre-defined path is constructed as represented in Fig 10. The pre-defined path track was constructed by pasting a 3.5 cm black tape on a white chart. The length of the track is set at 914.4 cm which consisting a curve line, sharp curve line, zigzag curve line and straight line make the track is complicated to follow. The path following is developed with nine critical point lines that were the circle with red as shown in Fig 10. There is two type of pre-defined path following that is large thickness of pre-defined path following and small thickness of pre-defined path following track. Critical point line here means the line that hard to be followed by the LEGO Mindstorms NXT robot and also described as a type of line that has a curve on it.

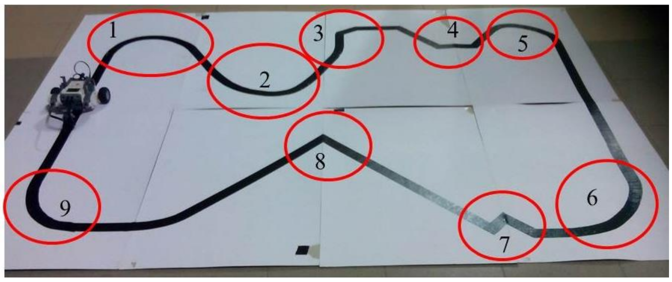

Fig 10. Pre-Defined Path Following

V. RESULTS AND DISCUSSIONS

This section describes the analysis of the validation from the experiment. The analysis is divided into two part where the first part will discuss and analysed the findings when the LEGO Mindstorms NXT is following the large thickness of the pre-defined path using Boolean logic, PID controller, fuzzy logic controller, non-improved fuzzy-PID controller and improved fuzzy-PID controller. The second part will discuss and analysed the findings when the LEGO Mindstorms NXT is following the small thickness of the pre-defined path using Boolean logic, PID controller, fuzzy logic controller, non-improved fuzzy-PID controller and improved fuzzy-PID controller. In this research, the different between non-improved fuzzy-PID controller and improved fuzzy-PID controller are non-improved fuzzy-PID controller is a normal fuzzy-PID controller method that has been used by the

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researcher while the improved fuzzy-PID controller is the proposed fuzzy-PID controller method that will improve the accuracy and velocity of the robot movement.

Table V shows the summary of the evaluation and validation result from the experimental approach for the large thickness of pre-defined path. The column of accuracy and velocity validate the implementation of the improved fuzzy-PID controller is successful in which for all controller methods evaluated, improved fuzzy-PID controller method achieve the best result compared to other methods. The result validates that velocity of the LEGO Mindstorm NXT robot is faster when follow the large thickness of pre-defined path.

Table V. Summarization of Experimental Result Validation for Large Thickness of Pre-Defined Path

Method	**Large Thickness (3.5 cm width of black tape)**		
	Accuracy (%)	**Time (s)**	**Velocity (cm/s)**
Boolean Logic	20	60	15.24
PID Controller	47	59	15.50
Fuzzy Logic Controller	57	44	20.78
Non-Improved Fuzzy-PID Controller	70	37	24.71
Improved Fuzzy-PID Controller	77	33	27.70

Table VI shows the summary of the evaluation and validation result from the experimental approach for small thickness of pre-defined path. The column of accuracy and velocity validate the implementation of the improved Fuzzy-PID controller is successful in which for all controller methods evaluated, improved fuzzy-PID controller method achieve the best result of velocity. As shown in Table VI, only non-improved fuzzy-PID controller and improved fuzzy-PID controller method successful finish follow the pre-defined path where the time taken to finish tracking the small thickness of pre-defined path for each method is 35 second and 25 second. Although non-improved fuzzy-PID controller successful finish tracking the small thickness of pre-defined path, however, improved fuzzy-PID controller method achieve the best result compared to other methods. The result also validates that velocity of the LEGO Mindstorm NXT robot is faster when following the small thickness of pre-defined path compared the large thickness of pre-defined path.

Table VI. Summarization of Experimental Result Validation for Small Thickness of Pre-Defined Path

Method	**Small Thickness (1.75 cm width of black tape)**		
	Accuracy (%)	**Time (s)**	**Velocity (cm/s)**
Boolean Logic	13	∞	∞
PID Controller	23	∞	∞
Fuzzy Logic Controller	30	∞	∞
Non-Improved Fuzzy-PID Controller	80	35	26.13
Improved Fuzzy-PID Controller	93	25	36.58

From the experimental results, only fuzzy-PID controller method can follow all the type of line whether in large thickness line or small thickness line. By using Boolean logic method, the robot movement is very inaccurate and slow. It is very traditional method for line follower robot and suitable for beginner to learn about line follower robot. PID controller and fuzzy logic controller method make the pattern of robot movement also inaccurate but better than Boolean logic method from aspects of accuracy and velocity. However, by using improved fuzzy-PID controller method, the pattern of robot movement is more accurate and faster. The significant improvement of the fuzzy-PID will increase the performance of the pattern of robot movement in line following application which is being use in wide area such as transportation, planetary exploration, surveillance, security and military targets tracking. In this research, the advantages or the effectiveness of improved fuzzy-PID controller method has been identified, which is the improved fuzzy-PID controller cover a more extensive scope of working conditions, and they are all the more effectively adjustable in normal dialect terms. In addition, a self-sorting out fuzzy controller can consequently channel an underlying surmised set of fuzzy rule and uses of improved fuzzy-PID controller enhance the quality variable.

VI. CONCLUSION

Usually, line follower robot might be able to follow the narrow and simple curve line, but with sharp curve line and zigzag line, the pattern of LEGO Mindstorms NXT robot movement will be not accurate and slow. The high complexity of line that is sharp curve line and zigzag line indeed give influence in robot movement. Only fuzzy-PID controller method can tracking all type of the line whether in large or small thicknesses of the line. At the end of the experiment, zigzag line and sharp curve line is identify as the type of line that will make robot movement is not accurate, chaotic and slow. Although the only single light sensor is installed in LEGO Mindstorms NXT, however, when the robot is controlled by the improved fuzzy-PID controller method, the robot can follow the path more accurate and faster. As a mention earlier, although a non-improved fuzzy-PID controller successful finish tracking the small thickness of pre-defined path, however, improved fuzzy-PID controller method achieve the best result which is the robot can follow all complicated path with high accuracy and velocity.

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