Cascade Controller Design For Steering Control Of Nonholonomic Autonomous Mobile Robot Vehicle

[1]S. Faiz Ahmed, D. Hazry, [2]F. Azim
[1]*Centre of Excellence For Unmanned Aerial Systems (COEUAS) Universiti Malaysia Perlis (UniMAP), Seriab, 01000, Kangar, Perlis, Malaysia.*
[2]*Hamdard University, Karachi Pakistan*
hazry@unimap.edu.my

Abstract- In this research article a cascade control system is presented for steering control of control of nonholonomic autonomous mobile robot vehicle. The propose system consist of a master controller and two slave controllers. The master controller is based on Fuzzy Logic Controller (FLC) which computes the required speed and angular speed needed by the two motors to drives the robot. Fuzzy logic is used to generate target trajectory movement. The two slave controllers are Proportional+Integral+Derivative (PID) controllers which ensured the desired speeds that needed for the both DC motors. PID controller parameters were tuned according to four ranges of speeds using model based tuning method. In addition, the control law is offered to select a suitable rule base for fuzzy controller in order to ensure the system is stable. The proposed cascaded controller is implemented on a nonholonomic mobile robot and the results have shown that, the proposed controller achieved the desired turning angle and the mobile robot tracks the target efficiently.

Keywords:nonholonomic autonomous mobile robot vehicl, Fuzzy Logic Controller, PID controller

I. INTRODUCTION

Autonomous navigation is the most important topic of artificial intelligence, various approaches have been tried to solve navigation problems [1]. The researchers have done studies to both holonomic and nonholonomic mobile robots [2-3]. Autonomous navigation is the ability of a mobile robot to move in an environment that is available to achieve a goal, without interacting with humans. In recent years, various new approaches to steering mobile robots have been developed. In 2004 Marichal , designed and present a fuzzy logic control system to decide how a mobile robot steer the wheel to achieve the desired orientation [4]. So, the desired target can be achieved simply by tuning the steering wheel towards the target. Besides that PID feedback controller is employed in the system to improve the performance of the system [5]. The purposed cascade fuzzy -PID controller is implemented on the mobile robot and the results showed the proposed method can achieve the desired turn angle to ensure that the autonomous mobile robot can reach the target set.

II. KINEMATIC MODEL OF THE NONHOLONOMIC MOBILE ROBOT

A. Differential Steering System

In the differential steering system to prevent slippage and achieve pure rolling motion, the mobile robot rotates around a point on the same axis in the two-wheel drive. This point is called the instantaneous center of rotation (ICR). By changing the drive speeds of two wheels move, the ICR will also be moved and will be followed by different trajectories [6]. Figure 1 shows the differential steering system of mobile robot.

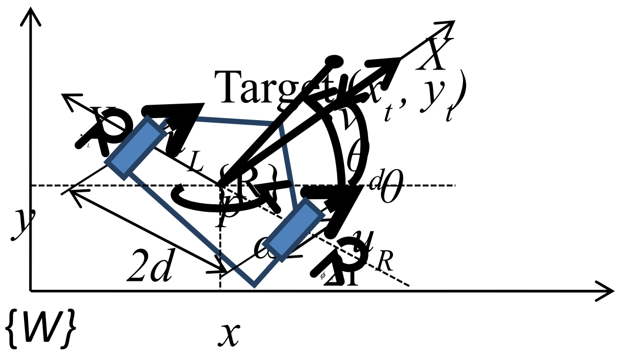


Fig 1: Differential steering system of the mobile robot

In this figure (x, y) is reference frame,(X, Y) is robot coordinates fame, R is the position of robot in (x, y), θ represents orientation angle of robot, r is wheel radius, 2d: distance between two wheels, uR/L are the speed of right and left wheels respectively, u, ω are the speed and angular speed of robot and $\dot{\phi}_R$ and $\dot{\phi}_L$: angular speed of right and left wheels respectively

The speed of the center of mass of the robot is orthogonal to the axis of the wheel. It is also assumed that the mass of wheels and wheel inertias is neglected. Meanwhile, center of mass of the mobile robot is located in the middle of the axis connecting the drive wheels.

p defines the origin of robot coordinate system with coordinate (x, y). θd is the angle between X-axis of world coordinate system denoted by {W} and the X-axis of robot coordinate system denoted by {R}.

The speed relative to the ground of the right wheel and the left wheel can be expressed as follows, respectively.

$$u_R = r\dot{\phi}_R = r \times \frac{\Delta\phi_R}{\Delta t} \quad (1)$$

$$u_L = r\dot{\phi}_L = r \times \frac{\Delta\phi_L}{\Delta t} \quad (2)$$

With, $\phi_{R,L}$ can be calculated b y using following equation:

$$\phi_{R,L} = \frac{x_{R,L}}{N_{R,L} \times 60} \quad (3)$$

where, NR,L are numbers of encoder per revolution of right and left wheel respectively, $x_{R,L}$ are the number of encoder pulses obtained from the encoders for the right wheel and the left wheel, respectively.

Therefore speed and the angular speed of a mobile robot related to the wheel speeds can be expressed as follows:

$$u = \frac{(u_R + u_L)}{2} = \frac{r}{2\Delta t}(\Delta\phi_R + \Delta\phi_L) \quad (4)$$

$$\omega = \frac{1}{2d}(u_R - u_L) = \frac{r}{2d\Delta t}(\Delta\phi_R - \Delta\phi_L). \quad (5)$$

Where in Equation (5), $u_R \rangle u_L$ and 2d is the width of the mobile robot from the center of the right wheel to the center of the left wheel.

III.Proposed Control technique for Mobile Robot

A cascade control system has been implemented to control the movement of the robot that consist a Fuzzy logic based master controller and two PID based slave controller for each DC motors as shown in Figure 2. Fuzzy logic is applied to generate target trajectory movement with the information extracted from vision system such as the distance of target and the orientation of target. We take the speed of mobile robot, for the robot speed could be fast, medium or slow. Using fuzzy logic terms, speed is a linguistic variable that takes the fuzzy sets: fast, medium or slow. The two slave Proportional+Integral+Derivative (PID) controllers are used to control the speed of each wheel as per desire value.

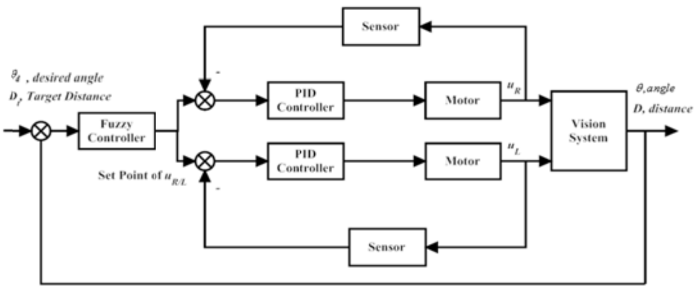


Figure 2: A cascade control system

IV.The Fuzzy Controller

A block diagram of the fuzzy controller is shown in Figure 3. The desired command signal$\theta_d$and D_t are transmitted from the vision system to the fuzzy controller inside the PC. The error between the command signal and the actual position, as well as the change in error of signal are calculated and fed into the fuzzy controller embedded in the DAQ. From the Equation (5), it can be seen that the different between the speed of the right and left wheels determines the turn speed. The fuzzy controller is designed to output PWM signal corresponding to u_R and u_L to the right motor and left motor respectively to control the mobile robot turn angle $\theta$to the desired angle θ_d and target distance D_t.

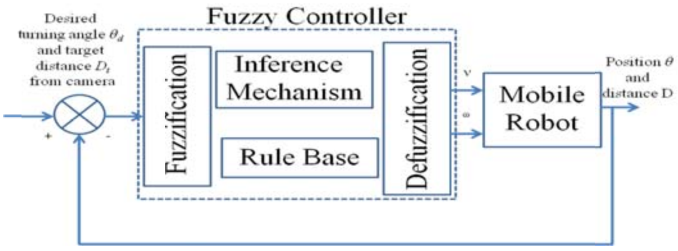


Figure 4: Block diagram of the fuzzy logic controller

The fuzzification procedure maps the crisp input values to the membership values between 0 and 1. Here we use three membership functions for target distance D_t and five membership functions desired angle θ_d. Figure 4 and Figure 5 illustrate the input membership functions for D_t and θ_d respectively.

Figure 4: Input membership functions for target distance Dt

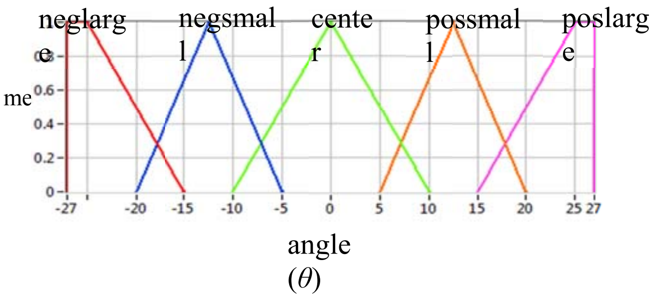


Figure 5: Input membership functions for desired angle θ

The control rules are designed based on expert knowledge and testing. Furthermore, the control rules also meet the trajectory requirements derived from PI control. For example, if θ_d is "poslarge" and is D_t "far", then the left motor should be much than the right motor, i.e., $u_L - u_R$ should be "more left" and speed $u_L + u_R$ should be "fast". Based on knowledge, we can obtain 15 rules. Table 1 represents conclusion understanding that the expert has about how to control the turn angle given the angle and distance as inputs. The input and output linguistic variables are shown in the table.

Table 1: Rules table for the steering system

		Angle of target (θ)				
		Neg-large	Neg-small	center	Pos-small	Pos-large
Distance of target (*D*)	far	more left, fast	left, fast	zero, fast	right, fast	more right, fast
	close	more left, medium	left, medium	zero, medium	right, medium	more right, medium
	too close	more left, slow	left, slow	zero, slow	right, slow	more right, slow

The de-fuzzification procedure maps the fuzzy output from the inference mechanism to a crisp signal. We use the "center of area" (COA) de-fuzzification method for combining the recommendations represented by the implied fuzzy sets from all the rules. The fuzzy logic controller then uses the Equation (6) to calculate the geometric center of this area. x donate the value for v or ω. Let $\int f(x)$ denote the area under the membership function $f(x)$.The COA method computes the crisp value to be

$$COA = \frac{\int_{x\min}^{x\max} f(x) \cdot x dx}{\int_{x\min}^{x\max} f(x) dx} \tag{6}$$

where COA is the center of area, x is the value of the linguistic variable, and x_{min} and x_{max} represent the range of the linguistic variable. Figure 6 and Figure 7 show the output membership functions. Note that the output PWM signals should be selected to meet the convergence requirements.

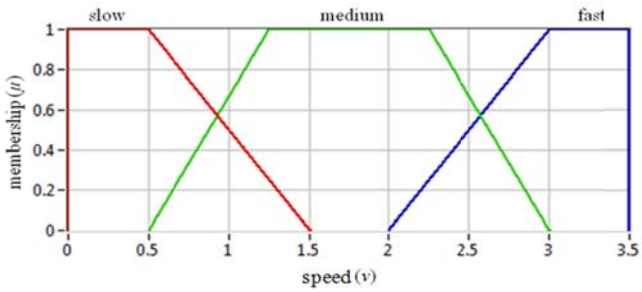


Figure 6: Output membership functions for the speed

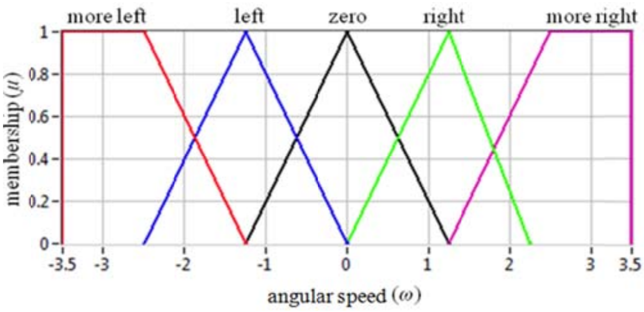


Figure 7: Output membership functions for the angular speed

V. The PID Controller

In the nonlinear control of mobile robots, the problems to achieve the desired speed for right wheel u_R and left wheel u_L are often caused by such factors as actuator constraint, time delay and other disturbances. One simple way to control the speed is to use a Pulse Width Modulation (PWM) pulse generator with PID feedback controller which can be used to improve the performance of the system.

The PID controller transfer function in Z Domain as shown below :

$$PID = \frac{g + g_1 z^{-1} + g_2 z^{-2}}{1 - z^{-1}} \quad (7)$$

Tuning of the PID controllers can be done using Model Based Method

VI.Model Based Method

In the Model based method the transfer function is derived from calculation of model parameters from a step experiment response. The Second order transfer functions are obtained for various segmentations of speed and PID parameters are calculated using classical controller design. This design method is known as pole assignment or pole shifting method.

The transfer function of a DC motor in discrete-time model is described as second order system by [7] as:

$$\frac{y(t)}{u(t)} = \frac{b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

a. Design with Classical Method and PID Control

During designing parameters for the PID controller, consider the feedback control system as shown in Figure 8.

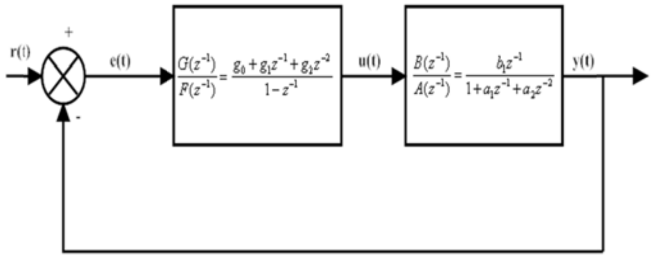


Figure 8: Feedback control system

The Close loop transfer function for this system can be write as :

$$\frac{y(t)}{r(t)} = \frac{b_1 z^{-1}(g_0 + g_1 z^{-1} + g_2 z^{-2})}{(1-z^{-1})(1+a_1 z^{-1} + a_2 z^{-2}) + b_1 z^{-1}(g_0 + g_1 z^{-1} + g_2 z^{-2})} \quad (8)$$

Using pole assignment method defined in [9], we compare characteristic equations with desired second order polynomial as:

$$(1-z^{-1})(1+a_1 z^{-1} + a_2 z^{-2}) + b_1 z^{-1}(g_0 + g_1 z^{-1} + g_2 z^{-2}) = 1 + t_1 z^{-1} + t_2 z^{-2} \quad (9)$$

with

$$t_1 = -2e^{-\xi\omega_n t} \cos T_s \omega_n \sqrt{1-\xi^2} \quad (10)$$

and $t_2 = e^{-2\xi\omega_n t}$ (11)

Thus, the Parameters of PID controller can be calculated by comparing the coefficients form (9). The PID parameters results for four different speeds of right wheel and left wheel are shown in Table 2.

Table 2: The result of the PID model based tuning for right wheel and left wheel

	Right Wheel PID Tuning			
PID	**0-1.0 RPS**	**1.0-2.5 RPS**	**2.5-3.0 RPS**	**3.0-3.5 RPS**
Kp	2.2769	25.248	41.079	176.7889
Ki	4.6592	16.6431	17.1421	152.4726
Kd	16.7932	210.1562	39.5797	431.8131

VII. Results & Simulation

a) Discussions

The speed and angular speed of mobile robot was determined by the number of encoder pulses for the right wheel and the left wheel. The PID controller is used to produce the same speed of the right wheel and left wheel in order to make the mobile robot move in straight line.

The robot system provides a stable speed property after implementing an onboard PID controller on free wheels time response experiments. Figure 9, 10, 11, 12, 13, 14, 15 and 16 show eight examples of the speeds time response with different speeds for left wheel and right wheel. The rising time increase when the desired speed is higher. The range of oscillations gets smaller for higher speeds. Through the experiences, the PID controller is also available for low speed such as 0.5 RPS except model based tuning method controller, but the oscillation is more drastic. The fast tuning PID controller shows the best result for free wheel time response experiments.

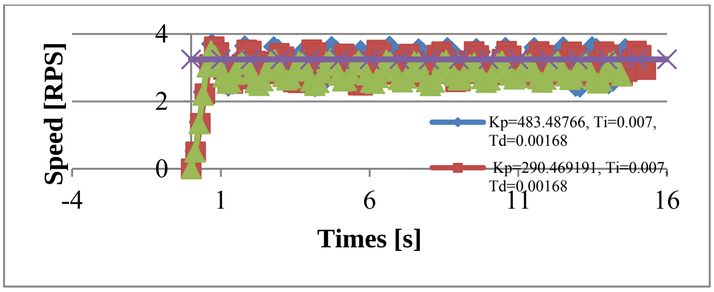


Figure 9: Time response of left wheel speed with 3.25 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

Left Wheel PID Tuning				
PID	**0-1.0 RPS**	**1.0-2.5 RPS**	**2.5-3.0 RPS**	**3.0-3.5 RPS**
Kp	1.9571	21.4094	42.5378	72.0978
Ki	4.286	24.088	15.916	34.523
Kd	18.8677	318.7978	82.9586	366.2725

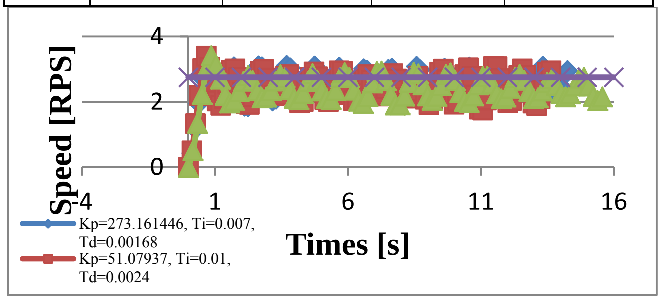


Figure 10: Time response of left wheel speed with 2.75 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

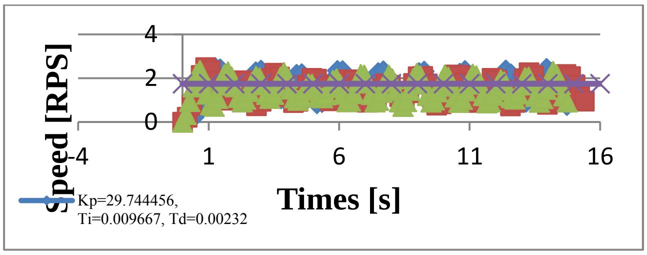


Figure 11: Time response of left wheel speed with 1.75 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

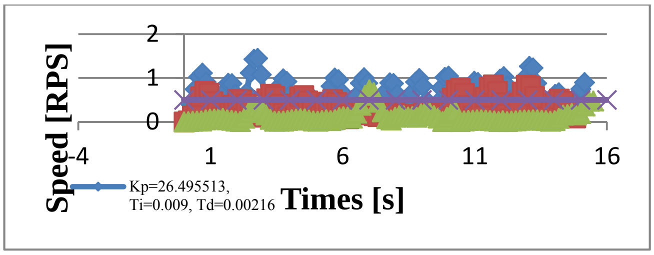


Figure 12: Time response of left wheel speed with 0.5 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

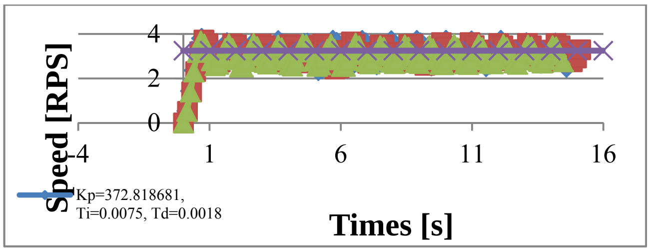


Figure 13: Time response of right wheel speed with 3.25 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

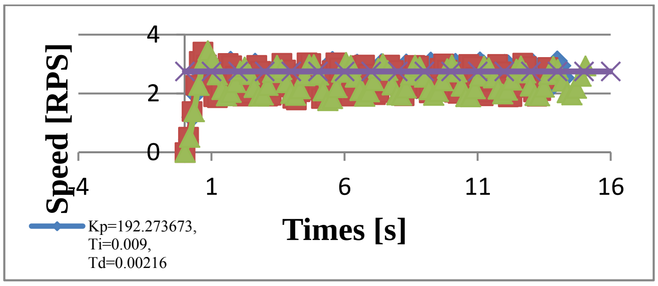


Figure 14: Time response of right wheel speed with 2.75 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

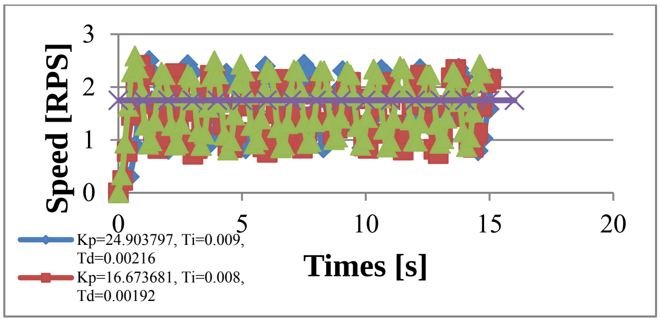


Figure 15: Time response of right wheel speed with 1.75 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

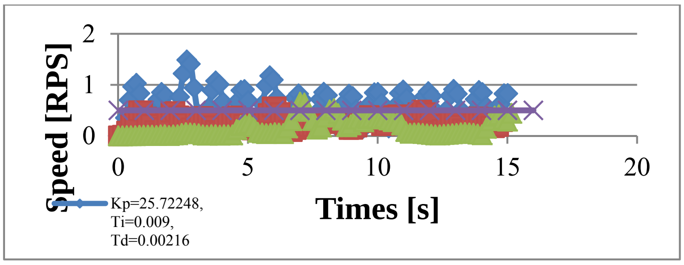


Figure 16: Time response of right wheel speed with 0.5 [RPS] step input, Fast Tuning blue, Normal Tuning red, Model Based Tuning green

Experiments were conducted to make a comparison of the test results between four ranges of speeds using Fast Tuning PID controller parameters in Table 2. The results are presented in Figures 17, 18, 19 and 20.

In the Figures, the horizontal axis is the traveling distance of mobile robot in centimeters and the vertical axis is the speeds of the wheel rotations defined by Equation (5.7) and Equation (5.8). The data plotted in the Figure 19 and 20 provide evidence that the speeds in wheel rotations of the Fast Tuning PID controller for the right wheel and the left wheel are in unstable condition at lower desired speed. The mobile robot shows high speeds from beginning of moving distance and does not move ahead to the target point in straight line tracking. In Figure 18 and Figure 19, we deduce that the small differences between the right wheel of speeds and the left wheel of speeds. Therefore, the mobile robot will move stably in tracking straight line.

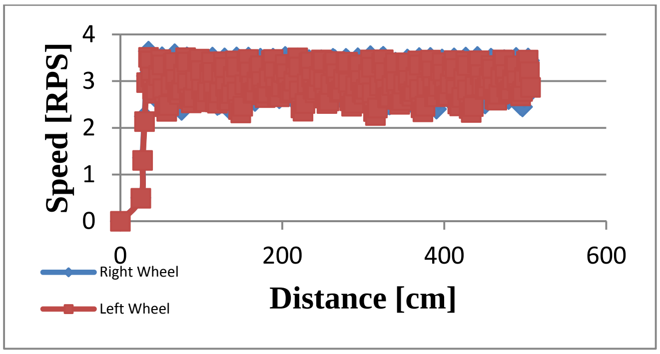


Figure 17: Comparison of the speeds in wheel rotations in straight line tracking at 3.25 [RPS] desired speed

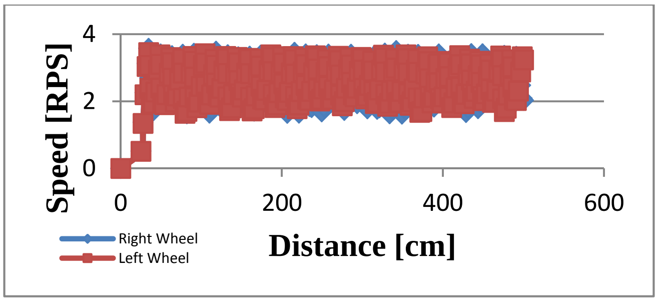


Figure 18: Comparison of the speeds in wheel rotations in straight line tracking at 2.75 [RPS] desired speed

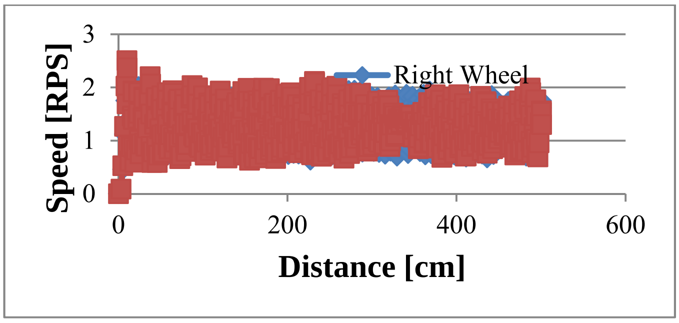


Figure 19: Comparison of the speeds in wheel rotations in straight line tracking at 1.75 RPS desired speed

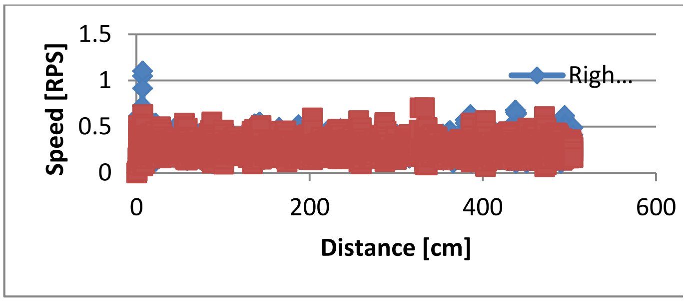
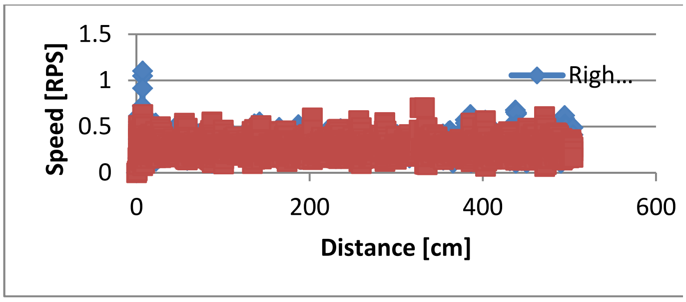


Figure 20: Comparison of the speeds in wheel rotations in straight line tracking at 0.5 RPS desired speed



From the experimental result studies, the mobile robot shows a stable movement in straight line tracking after using Fast Tuning PID controller for the right wheel and the left wheel for high desired speed as shown in Figure 17 and Figure 18 respectively. These PID control parameter were determined by performing fine tuning experiment explained. The system of two wheels of the mobile robot works concurrently with different PID controller parameter to perform a stable movement in straight line tracking for high desired speed.

VIII. Conclusion

In this article, an analysis and design of fuzzy control law for steering control of the developed nonholonomic mobile robot are presented. PID controller method is exploited to guarantee the stability of the straight line and turning trajectory. The proposed fuzzy controller with PID controller is implemented on the developed mobile robot. The system has performed well and satisfactory results are obtained which show that the proposed fuzzy controller and PID controller achieved the desired turn angle thus it can make the autonomous mobile robot moving to the target successfully.A system for two wheels of a mobile robot moves simultaneously with different parameters of PID controller to ensure the stability of movement in a straight line.

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