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Proportional Control Design on Mobile Robot for Leader-Follower Formation Using ZigBee Wireless Communication Module

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Abstract

Nowadays the development of technology is heading to industrial automation in many things, one of them is robotic. Robot is an alternative solution behind the limitation of human ability to do their activity continuously. One of interesting thing in robotic is leader-follower concept. The leader-follower concept is a thing that is tried to be implemented in robot to adapt human habit. Leader-follower is a simple concept that placed one of the robot acts to give command to another robot. In order to get good respon and small error from the system for the mobile robot, it needs controller that can organize the velocity of robot depend on the differences of distance and angle. PID is choosen as controller on mobile robot system because of it capability to produce fast response. In this paper, control system of mobile robot is not embedded in the robot but located in station ground. In order to build the communication, Zigbee is used for transferring data from robot to ground station or ground station to robot. The challenge is how to integrate control system, measurement and communications in a short time. Both leader and follower only execute Pulse Width Modulation that they got from ground station, and then PWM is used to rotate DC motor. The test is done by given three initial condition, the first initial condition is Straight, second is tilted to the right, and third is tilted to the left. The overall results of the three tests then processed in order to determine how far follower deviates from the leader. Formation that formed between leader and follower robot is in line formation or in other words, if the robot moves along the Y axis to determine the deviation of follower to leader, it can be seen from the error position x from follower. Based on measurement, the best response of the system is shown by proportional gain with the value of 1.5048. The error position x result of the proportional gain are 1.22% for initial conditions “straight”, 2.38% for initial condition “Tilted to the Right” and 2.26% for initial condition “Tilted to the Left”.

Keywords: Mobile Robot, Leader-Follower, PID Controller, Zigbee

1. Introduction

In recent years there were increasing amount of research on the subject of mobile robotics. Mobile robot has many advantages in helping industrial process. It can move from one position to another position depend on its setting. In the few researches, mobile robot try to be combined with another mobile robot using leader-follower concept in order to complete their own goal [1, 2].

Generally, leader-follower concept is inspired by swarming behaviour of living being like flocks bird, herds of wildebeest and colonies of bacteria. The main important concept in leader-follower robot is control formation between leader robot and follower robot, hence the follower can avoid their formation to the leader robot [2-4]. Various type of formation can be implemented on mobile robot depend on the exploration area. For instance, indoor mobile robot typically not using GPS for determining the positions. Because of it is operated indoor, it can generate large error from the measurement of position. Hence, indoor mobile robot using ultrasonic sensor and compass may be one of the choice. The usage of ultrasonic sensors classified on line of sight measurement, so there is limitation on measuring distance between robots. This constrain should be taken into account during the motion planning coordination and control design [5].

Leader-follower formation control proposed in [6], it used infrared as a sensor, hence there was limitation to measure distance over 30 cm. Another research about leader-follower formation control proposed in [7] also showed deficiency in detecting leader position, because it only used ultrasonic sensor and reflector to detect leader’s position. Therefore, this research will be used ultrasonic sensor (HCS 04) to measure the distance and compass sensor (CMPS 10) to measure the angle difference of both leader and follower. After get distance and angle value, can be found the position of leader and follower using trigonometry method.

In this paper, control system of mobile robot is not embedded in the robot but located in station ground. In order to build the communication, Zigbee is used for transferring data from robot to ground station or ground station to robot [8]. The challenge is how to integrate control system, measurement and communications in a

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short time. Both leader and follower only execute Pulse Width Modulation that they got from ground station, and then PWM is used to rotate DC motor. To complete this task, Zigbee have to configure as coordinator and as end device to differentiate who is the master and who is the slave [9].

2. Mobile Robot

Mobile robot is designed based on figure 1. Follower arranged with additional ultrasonic sensor (HC SR04) and compass (CMPS10), the purpose is to detect where the leader is. While leader arranged only with compass (CMPS10). Both leader and follower equipped with wireless communication module (Zigbee) to facilitate communication between mobile robot and ground station.

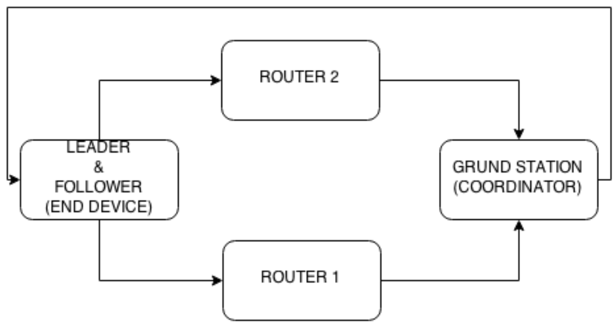

Fig. 1. Communication Block System

Block diagram of the overall system is divided into three parts: node end device, node router and node coordinator.

a. Node Coordinator
   This block system consist of Arduino Mega and wireless communication module as a coordinator. Function of this block is to monitor and process data that received from router.
b. Node Router
   This block is part of Node Coordinator too but this block has different function. Function of this block is to receive data from leader and follower. This block consist of two wireless communication module and Arduino Mega
c. Node End Device
   Block system at this node is the leader and the follower robot that equipped with wireless communication module, CMPS10, HC SR04, LCD, lithium battery, gear box, motor driver and arduino Uno

2.1. Mobile robot communications design

Communication flowchart that is build enable robot to receive and transmit data. But in this system both leader and follower only receive the result of control process that is Pulse Width Modulation (PWM).

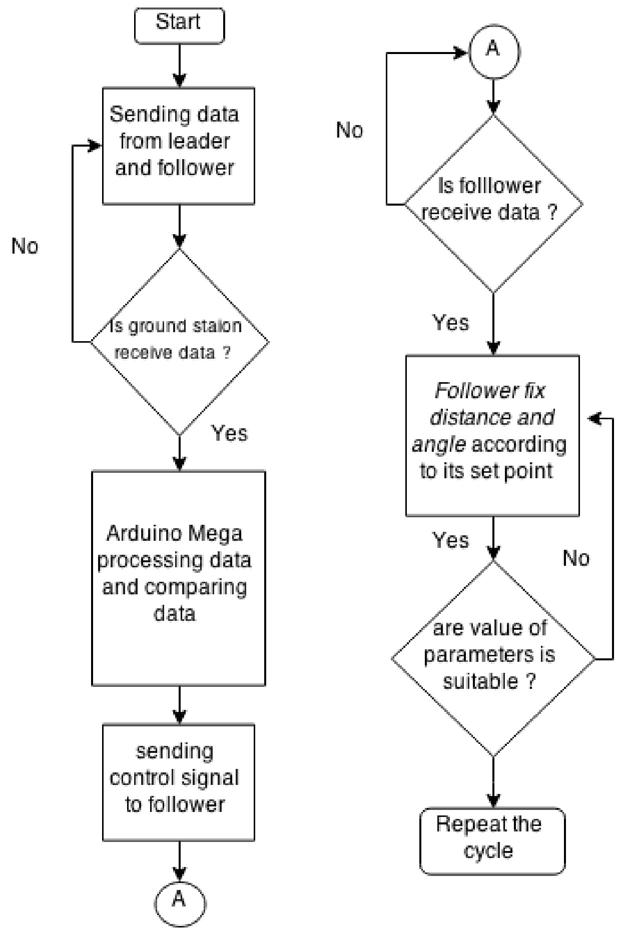

Fig. 2. Communication Flow Chart System

2.2. Proportional Control

The signal Control of PID controller is shown by this equation:

$$u = K_p e + k_i \int e \, dt + K_d \frac{de}{dt} \tag{1}$$

The variable ‘e’ represent the tracking error which equal with the difference between desired input value and actual output. This error signal ‘e’ will be sent to the PID controller, and controller computes both the derivative and integral of this error signal. The signal ‘u’ will be sent to the plant and the new output will be obtained. Equation (1) shown the complete of PID controller scheme. But if only use proportional control, the equation will be:

$$u = K_p e \tag{2}$$

The signal ‘u’ in equation (2) now equal to the proportional gain (Kp) times the error.

3. Result and Discussions

3.1. Implementation of Control

Before defining control for the system, we need to find transfer function of DC motor. By finding parameter like maximum torque and maximum angular velocity we it can get the transfer function of DC motor [10].

$$\frac{\theta_m(S)}{E_a(S)} = \frac{\frac{Kt}{R_a J_m}}{S[s + \frac{1}{J_m}(D_m + \frac{K_b K_t}{R_a}]} \tag{3}$$

With : θ_m = angular position
E_a = input voltage
D_m = viscous damping at the armature
K_t = motor torque constant
R_a = armature Resistant
K_b = electromotive constant

To find value of those parameter, we have to know relation between every parameter. If a dc voltage, E_a, is applied, the motor will turn at a constant angular velocity, com, with a constant torque, Tm. The following relationship exists when the motor is operating at steady state with a dc voltage input:

$$\frac{R_a}{K_t} T_m + K_b \omega_m = E_a \tag{4}$$

Solving for Tm yields

$$T_m = -\frac{K_b K_t}{R_a}\omega_m + \frac{K_t}{R_a} E_a \tag{5}$$

With : T_m = maximum torque
ω_m = maximum angular velocity

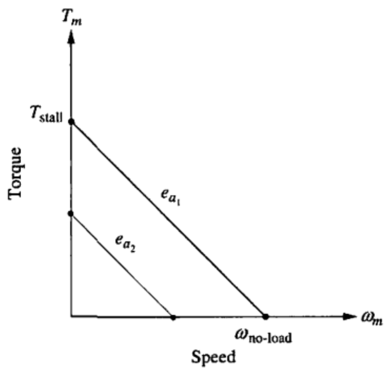

Fig. 3. Torque-speed curves with an armature voltage, Ea, as a parameter

Equation (5) is a straight line, T_m vs ω_m, and is shown in Figure. 3 This plot is called the torque-speed curve. The torque axis intercept occurs when the angular velocity reaches zero. That value of torque is called the stall torque, T_{stall} Thus,

$$\frac{K_t}{R_a} = \frac{T_{stall}}{E_a} \tag{6}$$

The angular velocity occurring when the torque is zero is called the no-load speed Thus,

$$\omega_{no-load} = \frac{E_a}{K_b} \tag{7}$$

Table 1
Inertia Motor's Measurement

Mass (Kg)	r (m)	N1	N2	Jm (Kg.m^2)
0.00633	0.02	8	64	1.98x10^{-8}

Table 2
Torque Measurement

Massa (Kg)	Gravitation	Force (N)	r(m)	Torque (N.m)	Ea (V)	kt/Ra
0.75	9.8	7.35	0.02	0.147	10.37	0.0141755

We can use Table.1 and Table.2 to determine the transfer function. So, the transfer function is:

$$\frac{\theta_m}{E_a} = \frac{716000\ S}{S^2 + 60400\ S} \tag{8}$$

We are searching for $\frac{\omega_m}{E_a}$ form, so to change Equation (8), we have to use a differentiator. So the equation will be:

$$\frac{\omega_m}{E_a} = \frac{716000}{S + 60400} \tag{9}$$

With root locus method can be known the pole's moving on close loop system because of the raising of gain. Figure 3 show the plot of transfer function using root locus, there are a pole at -60.400 that move to the left side. From figure 3 we know that the system can be controlled only by using proportional control. Since the pole's move toward to -∞, every gain that is given to the system will make system stable. Hence, tuning Proportional gain is done to find the best value of proportional gain.

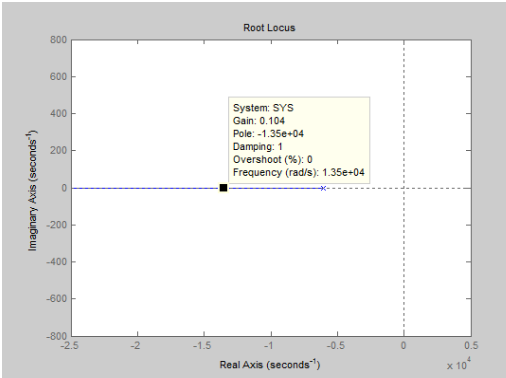

Fig. 4. Root Locus Transfer Function

Table 3
Tuning Proportional Gain

Gp	Tr (S)	Ts (S)	Peak Amplitude	OS (%)	Steady State
0.11085	1.57 x10^{-6}	2.80 x10^{-6}	0.558	0	0.558
0.2157	1.02 x10^{-6}	1.82 x10^{-6}	0.718	0	0.718
0.31142	7.55 x10^{-6}	1.38 x10^{-6}	0.787	0	0.787
0.40408	6.28 x10^{-6}	1.12 x10^{-6}	0.827	0	0.827
0.5046	5.21 x10^{-6}	9.28 x10^{-6}	0.857	0	0.857
0.60404	4.46 x10^{-6}	7.94 x10^{-6}	0.877	0	0.877
0.72403	3.80x10^{-6}	6.76 x10^{-6}	0.896	0	0.896
0.82994	3.36 x10^{-6}	5.98 x10^{-6}	0.908	0	0.908
0.90922	3.09 x10^{-6}	5.50 x10^{-6}	0.915	0	0.915
1	2.83x10^{-6}	5.04 x10^{-6}	0.922	0	0.922
1.1428	2.50 x10^{-6}	4.45 x10^{-6}	0.931	0	0.931
1.2525	2.30 x10^{-6}	4.09 x10^{-6}	0.937	0	0.937
1.3113	2.2 x10^{-6}	3.91 x10^{-6}	0.94	0	0.94
1.5048	1.93 x10^{-6}	3.44 x10^{-6}	0.947	0	0.947
2.531	1.17 x10^{-6}	2.09 x10^{-6}	0.968	0	0.968

Based on Table 1, the fastest response from proportional gain is 2.531, but when it is implemented on mobile robot that value cause wind up effect on the mobile robot. With proportional gain 2.531, error system will increased larger, because error directly proportional with proportional gain and produce excessive response. Hence, 1.5048 is selected as proportional gain and cause more stable conditions than 2.531 as proportional gain.

3.2. Test Result

3.2.1. Proportional gain = 0.2571

The test result can be seen on figure 4. Figure 4 shows data from test for three conditions: Straight (Green Line), Tilted to The Right (Blue Line) and Tilted to The Left (Yellow Line). Parameters that is measured include angle error and position (x, y) error from robot while the resulting output is PWM.

The results shown by Figure 4(b), there is no difference in the value of the PWM. It happen because there is no angle error more than 4° or less than -4°. From the beginning until the end, the Left PWM and the Right PWM has the same value, it indicates that follower moves straight along the track.

At the time of 0-900 ms and 1200-3975 ms, the results shown by Figure 4(f), there is any difference in the value of the PWM, that means follower were turning its position from tilted to the left to straight position. After 1425 ms, follower move straight (right PWM=left PWM) because there is no angle error more than 4° or less than -4°. PWM moves from higher value to lower value, it indicates that Y axis error become smaller.

Then when the time of 0-600 ms and 1200-3675 ms, the results shown by Figure 4(d), there is any difference in the value of the PWM too. That means follower were turning its position to straight position.

3.2.2. Proportional gain = 1.5048

The test result can be seen in Figure 5. Figure 5 shows data that using proportional gain = 1.5048. Parameters that is measured include angle error and position (x, y) error from robot while the resulting output is PWM.

The results shown by Figure 5(b), there is no difference in the value of the PWM. It happen because there is no angle error more than 4° or less than -4°. From the beginning until the end, the Left PWM and the Right PWM has the same value, it indicates that follower moves straight along the track. The different with chart in Figure 4(b), the value of PWM (straight) in Figure 5(b) has longer range of PWM. It is started from18 until 26.

At the time of 0-1200 ms and 1575-1875 ms, the results shown by Figure 5(f), there is any difference in the value of the PWM, that means follower were turning its position from tilted to the left to straight position. After 1425 ms, follower move straight (right PWM=left PWM) because there is no angle error more than 4° or less than -4°. PWM moves from higher value to lower value, it indicates that Y axis error become smaller.

Then when the time of 0-1875 ms and 2475-3675 ms, the results shown by Figure 5(d), there is any difference in the value of the PWM too. That means follower were turning its position from tilted to the right to straight position.

3.2.2. Proportional gain = 2.571

The test result can be seen in Figure 6. Figure 6 shows data that using proportional gain = 2.571. Parameters that is measured include angle error and position (x, y) error from robot while the resulting output is PWM.

The results shown by Figure 6(b), there is any difference in the value of PWM at the time 1725-2475 ms. It happens because follower get bigger proportional gain. So, error that is received by follower will proportionally increase. Besides that, the range value of PWM is longer than PWM that use less gain. It is started from 15 until 36.

At the time of 0-300 ms , the results shown by Figure 6(f), there is any difference in the value of the PWM, that means follower were turning its position from tilted to the left to straight position. And then the max PWM in the system is 60, so if there is PWM that has reached that value, it indicated that the value of error is high.

Then chart in Figure 6(d) show the same analysis with chart in Figure 4(d) and Figure 5(d). The differences of Left PWM and Right PWM indicate that follower were turning its position from tilted to the right to straight position.

3.2. Overall Result

The overall results of the three tests then processed in order to determine how far follower deviates from the leader. Formation that formed between leader and follower robot is in line formation or in other words, if the robot moves along the Y axis to determine the deviation of follower to leader, it can be seen from the error position x from follower. Here is the error of the X axis of each test.

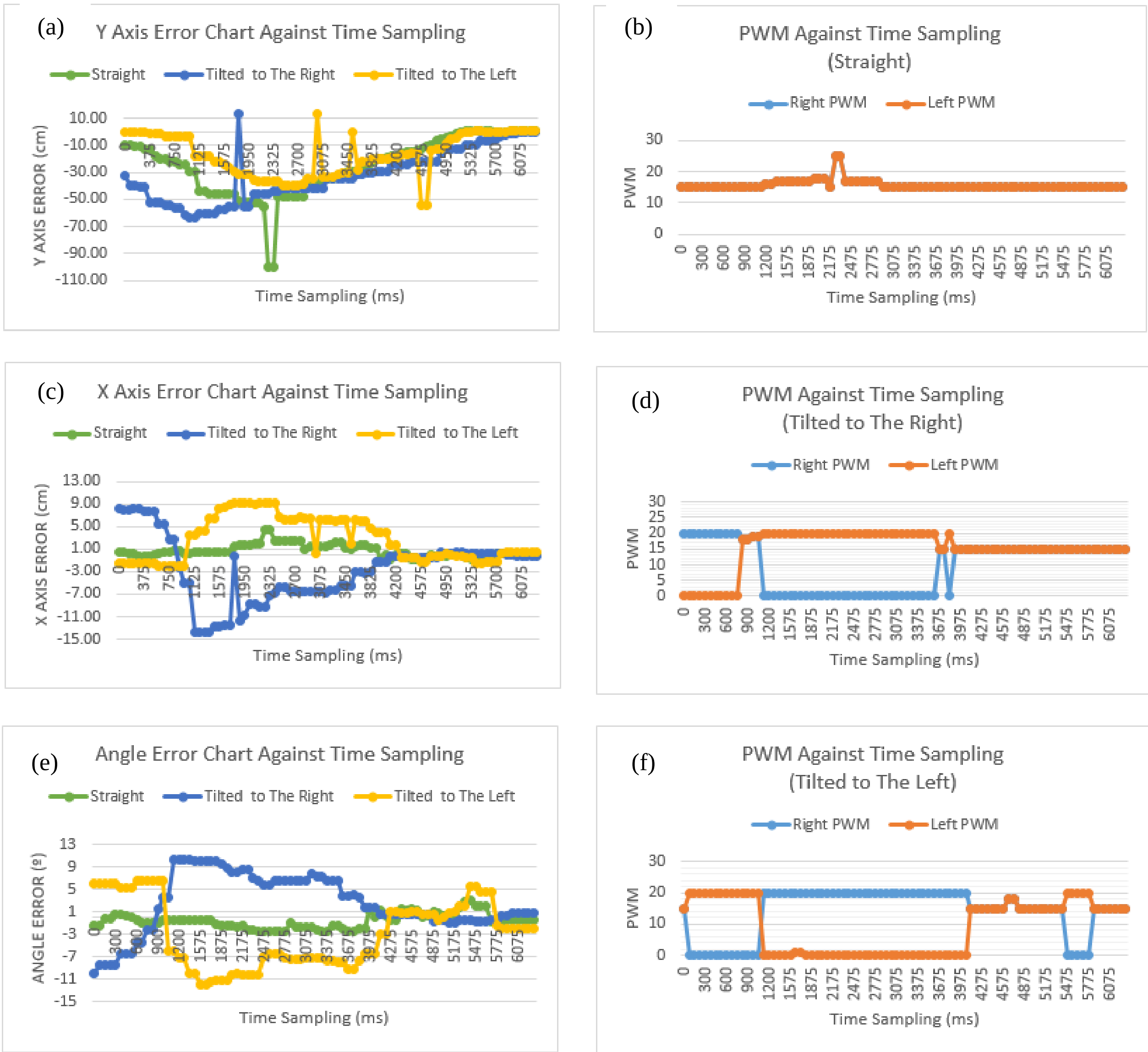

Fig. 5. Proportional gain 0.2571 Test Result (a) Y axis error (b) PWM with initial condition straight (c) X axis error (d) PWM with initial condition tilted to the right (e) Angle error (f) PWM with initial condition tilted to the left

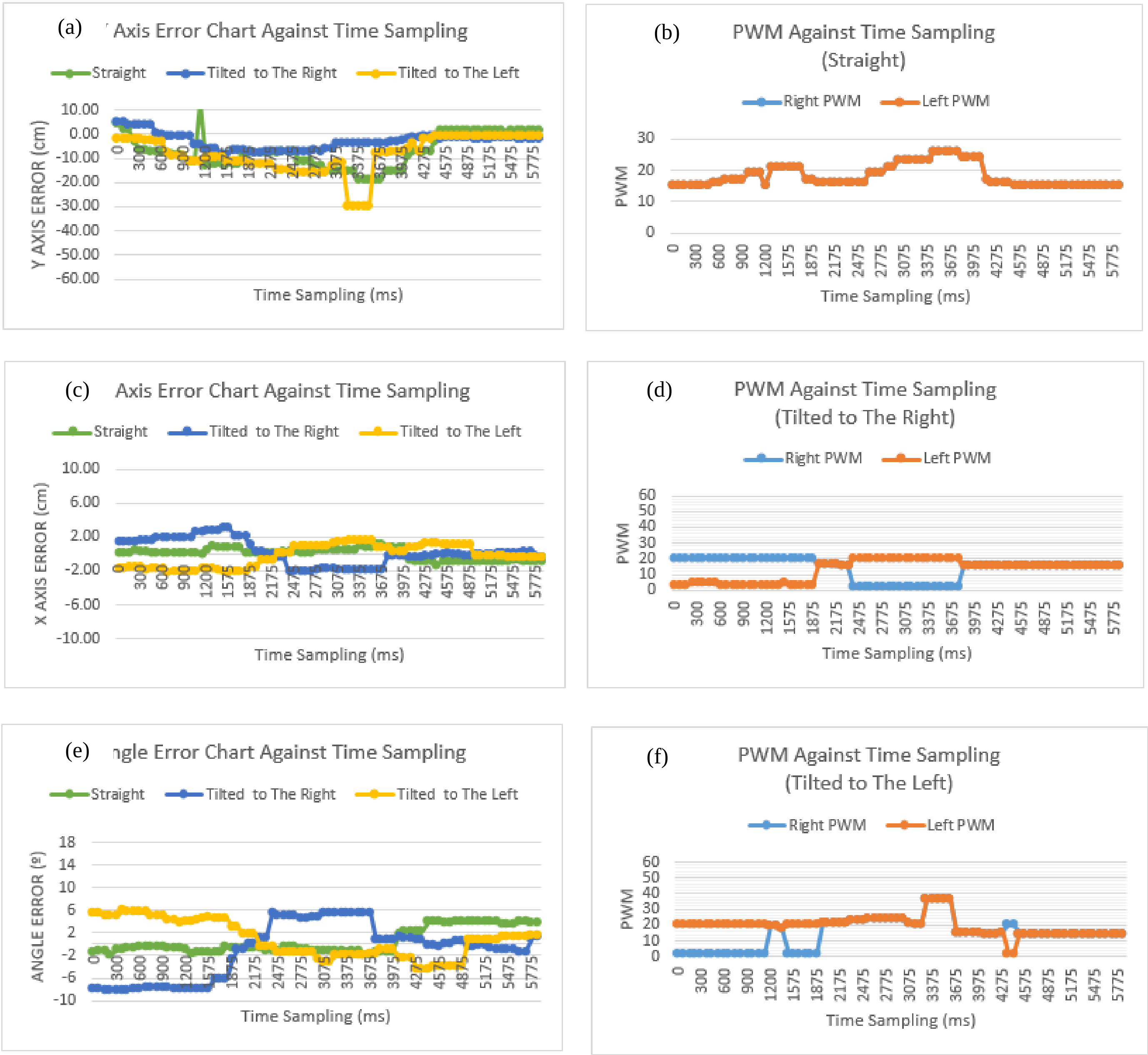

Fig. 6. Proportional gain 1.5048 Test Result (a) Y axis error (b) PWM with initial condition straight (c) X axis error (d) PWM with initial condition tilted to the right (e) Angle error (f) PWM with initial condition tilted to the left

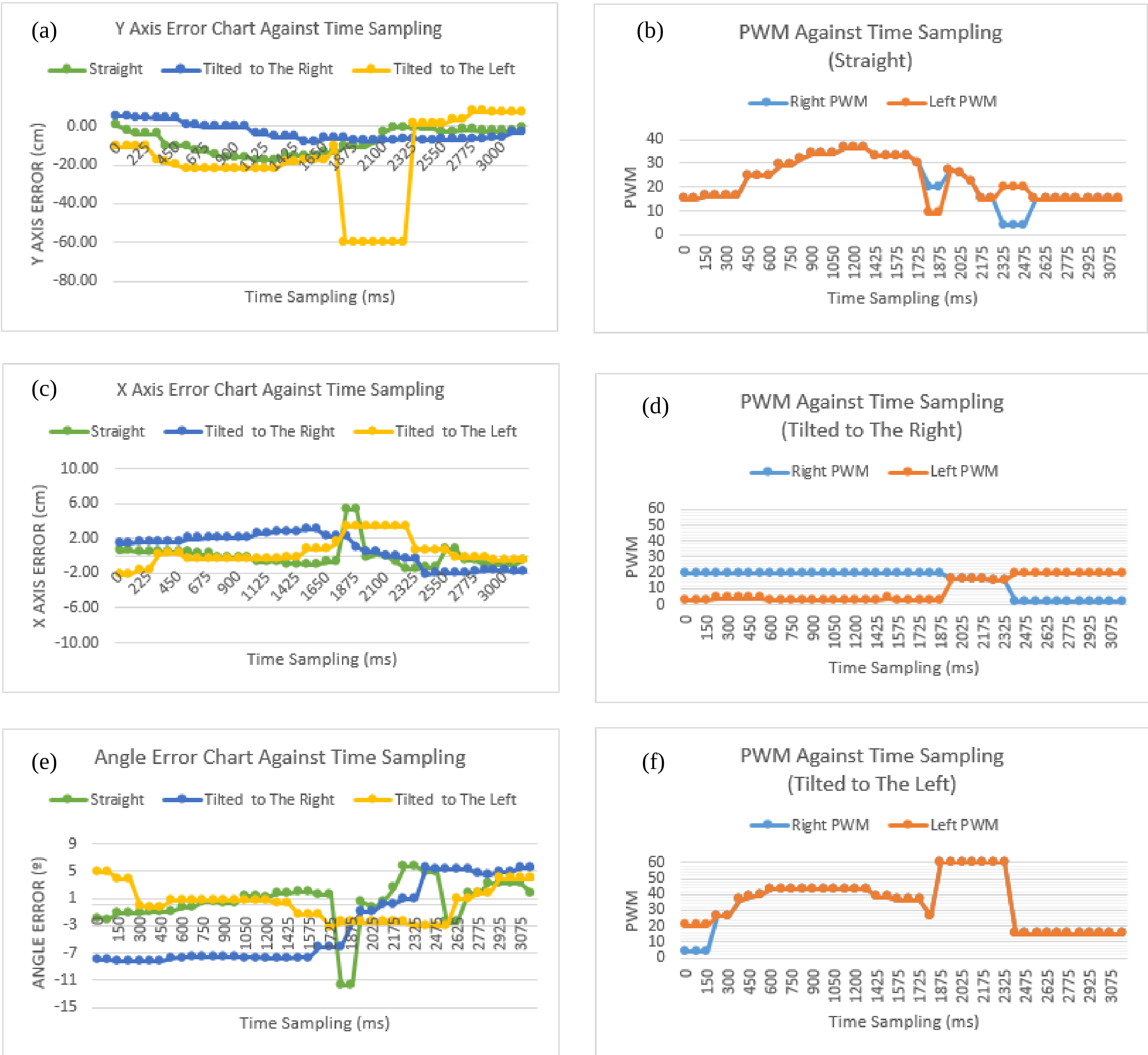

Fig. 7. Proportional gain 2.531 Test Result (a) Y axis error (b) PWM with initial condition straight (c) X axis error (d) PWM with initial condition tilted to the right (e) Angle error (f) PWM with initial condition tilted to the left

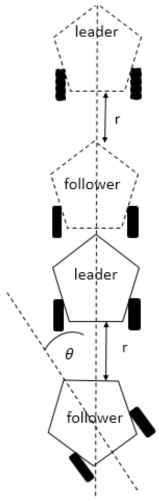

Fig. 8. Illustration movement of the robot

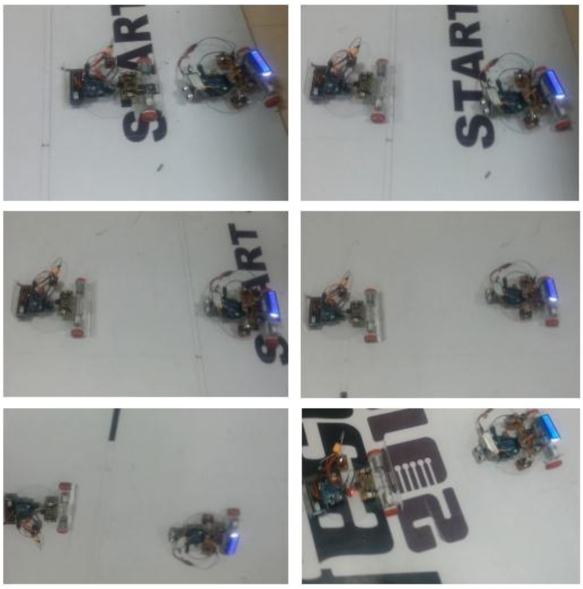

Fig. 9. Implementation result

Table 4
. Overall X Axis Error

Initial Conditions	Error X		
	Proportional gain = 0.2571	Proportional gain = 1.5048	Proportional gain = 2.531
Straight (-4º to 4º)	1.84%	1.22%	1.75%
Tilted to The Right (>4º)	9.27%	2.38%	4.87%
Tilted to The Left (<-4º)	7.17%	2.26%	2.18%

From Table 2 the lowest error position X for initial condition “Straight” is when follower use proportional gain = 1.5048. Then the lowest error position X for initial condition “Tilted to The Right ” is when follower use proportional gain = 1.5048. The last for initial condition “Tilted to The Left”, the lowest error position X is when follower use proportional gain = 2.531. This follower robot use CMPS10 to monitor the angle. Error of the angle will getting bigger if follower turn away the north poles (move to the right) and error of the angle will getting smaller if follower turn near the north poles (move to the left). The reason why proportional gain = 2.531 is better than proportional gain = 1.5048 to be implemented in the follower when the initial condition “Tilted to The Left” is because when the initial condition “Tilted to The Left” the error is low. So, the bigger proportional gain will fix the position of the follower faster. However, the best proportional gain is 1.5048 because in others initial condition, it gives lower error than other proportional gain.

4. Conclusion

Proportional control that has been implemented into the leader and follower robot, the best proportional gain is 1.508 because with that value, follower will has smaller error that the other proportional gain. When initial condition is "Tilted to The Left", proportional gain that produce lowest error is 2.531. It happens because at the initial condition "Tilted to The Left" the error is low. So, the bigger proportional gain will fix the position of the follower faster. However, this system is still limited in measuring distance over 4 meters.

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