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CONTROL OF WHEELED MOBILE ROBOT IN RESTRICTED ENVIRONMENT

CHANG YONG EN

Thesis submitted in fulfillment of the requirements
for the award of the degree of Bachelor of Engineering (HONs) in Mechatronic
Engineering

Faculty of Manufacturing Engineering
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ABSTRAK

Projek ini adalah satu kajian kawalan robot mudah alih beroda dalam persekitaran yang terhad. Sebuah robot mudah alih beroda dengan 3 roda adalah rekaan dan ia adalah kawalan oleh terbitan kawalan daya aktif berkadar (PD-AFC) untuk bergerak dalam persekitaran terhad pra-dirancang untuk melaksanakan ralat sifar landasan yang betul. Parameter kinematik dan dinamik daripada robot mudah alih akan dipertimbangkan. Untuk pengawal, sistem kawalan dengan dua gelung, gelung luar dan dalam direka untuk mengawal robot mudah alih yang beroda. Kabur pengawal logik dilaksanakan dalam SIMULINK untuk menganggarkan Inertia Matrix yang akan digunakan untuk mengira tork sebenar digunakan pada robot mudah alih yang beroda. Robot mudah alih diuji dalam bulat trajektori. Hasil carian telah direkodkan dan dianalisis Walau bagaimanapun, pergerakan robot mudah alih yang beroda di jalan yang sebenar dan jalan yang dikehendaki dibandingkan.

ABSTRACT

This project is a study of control of wheeled mobile robot in restricted environment. A wheeled mobile robot with 3 wheels is fabricated and it is control by a proportional derivative active force control (PD-AFC) to move in a pre-planned restricted environment to perform minimum track error. The kinematic and dynamic parameters of the mobile robot are considered. For the controller, a control system with two loops, outer and inner loop is designed to control the wheeled mobile robot. Fuzzy logic controller is implemented in the SIMULINK to estimate the Inertia Matrix that will be used to calculate actual torque applied on the wheeled mobile robot. The mobile robot is tested in circular path. The results are recorded and analyze. However, the movement of the wheeled mobile robot in actual path and desired path are compared.

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LIST OF SYMBOLS

v	Linear velocity
w	Angular velocity
I	Moment of inertia
τ_i	Torque
I	Inertia Matrix
$\ddot{\theta}$	Angular acceleration

LIST OF ABBREVIATIONS

PID	Proportional-Integral-Derivative
FLC	Fuzzy logic control
AFC	Active force control
WMR	Wheeled mobile robot

CHAPTER 1

INTRODUCTION

1.1 Introduction

Mobile robot plays an important role in society today. There are several types of mobile robot, such as legged, wheeled and tracked mobile robot (Elyoussef, De Pieri, Moreno, & Jungers, 2012). In this technology world, mobile robot became a great helper for human. Wheeled mobile robots are used in many applications especially in factory and some restricted environments that human cannot perform. With the help of the mobile robot, the efficiency to complete a task will be enhanced. For example in production line, robot may shorten the time taken to make the product and reduce manpower (Abdalla, 2013). Moreover, the wheeled mobile robot cannot be use only in factory but it also can be implemented in the road environment. To make sure that the mobile robot will arrive safely in the end point, a pre-planned path is set. The mobile robot is able to follow the planned motion. Many researches are done on the motion control of wheeled mobile robot, such as high tracking accuracy (Deng, Yao, Zhu, Wang, & Yang, 2014).

The motion of the wheeled mobile robot is controlled by controller such as Proportional-Integral-Derivative (PID), Fuzzy logic control (FLC), Active force control (AFC). PID controller is the mostly used controller in industry because of its simplicity (Deng et al., 2014) Besides that, AFC also is a good controller that can minimize the tracking error effectively (Ali, Yusoff, Hamedon, & Yusssof, 2015). By implementing a useful controller, the motion of the wheeled mobile robot will become stable and accurate. Moreover, the mobile robot will be able to move in different types of trajectories with zero track error.

In this research, the Active force control (AFC) algorithm will be implemented to a three wheeled mobile robot to move in different types of restricted environments with zero track error. The motion of the mobile robot is planned and the actual with desired paths of the wheeled mobile robot are compared. Moreover, both kinematic and dynamic modelling of the mobile robot is considered. In this project, it is only focus on the three wheels differential drive mobile robot which will be tested in circular and rectangular path.

1.2 Problem Statement

The main problem of the path control mobile robot is the big tracking errors that occur in its actual trajectory. Nowadays, mobile robot helps the human to do many works, especially some dangerous and repeated works. To control the wheeled mobile robot in restricted environment such as road, and factory; the safety factor should be considered. To prevent collision, the mobile robot should have an approximate zero tracking error performance. From the figure 1, it shows the desired trajectory path and actual trajectory path. The different between desired trajectory and actual trajectory is the tracking error. If the mobile robot does not move in the desired trajectory, collision may occur. Thus, to avoid obstacle collision occur, the mobile robot should move in its planned path with minimum tracking error.

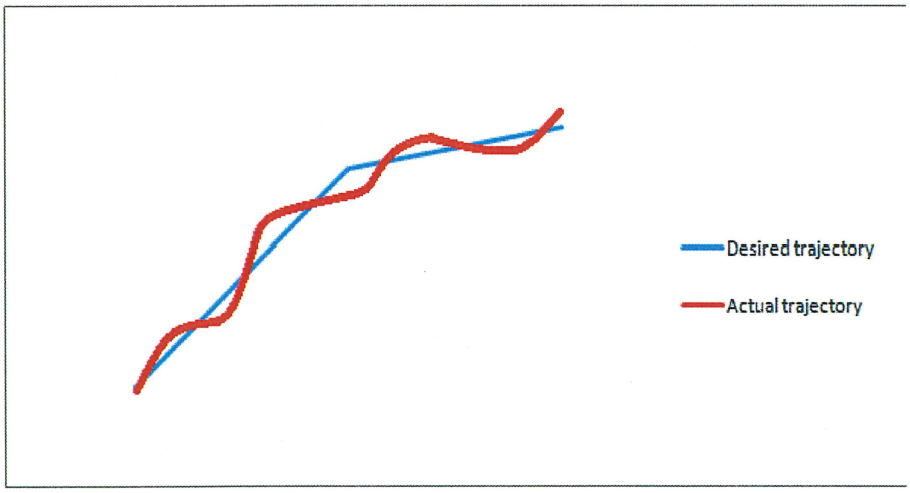


Figure 1.1 Desired trajectory and actual trajectory path of the mobile robot

The next problem of the controlled mobile robot is happed when we use Tele-operated system which controls the robot remotely by human and cause inaccurate control operation of mobile robot. Tele-operated mobile robot control system may need the manpower and some error un-estimated disturbances may occur during the control operation. Therefore, it will affect to the efficiency of the mobile robot to complete their task, where the mobile robot should move in the desired path with a useful controller. An appropriate controller such as PID controller and AFC controller can increase the predictability of the mobile robot's behaviour to decrease tracking errors and can make sure that the control of mobile robot is in robust enough. Besides, it also can speed up the mission of the mobile robot: e.g. in the factory, with the present of these mobile robots, the time taken for the mobile robot to complete the task will be shorter, thus, the productivity will increase. Moreover, a proper controller can increase the efficiency of the mobile robot to complete its task.

1.3 Objective

The main objectives of this work are:

1. To fabricate a three wheeled mobile robot with two differential wheels and one castor wheel.
2. To apply the Proportional Derivative-Active force control (PD-AFC) algorithm with different types of restricted environments.
3. To control wheeled mobile robot in restricted environment with minimum track error.

1.4 Project Scope

The project focuses on three wheels mobile robot. The mobile robot consists of two differential wheels and one castor wheel. For the differential wheel, the speed of the wheels are driven by DC-Brush-motors, so when the both wheels rotate at different speed, the can turn to left and right. While for castor wheel, it enables the mobile robot to move speed freely.

As mobile robot is use in factory or on the road, for handling some goods from one place to another place, the mobile robot must sustain high load. For my project, the mobile robot is able to sustain medium load, which is around the 50kg while moving in the planned trajectory.

Besides, for the project, the velocity of the mobile robot is slow. It can move with velocity up to 0.35m/s. This is to make sure that the mobile robot is able to move smoothly in correct path. Moreover, it increases the safety factor if the mobile robot moves with appropriate velocity e.g. it can minimize the impact of collision.

Furthermore, the wheeled mobile robot is controlled in restricted environment, where it should moves in complex path; but for the project, the mobile robot control will be performed on circular path.

1.5 Project Flow Chart

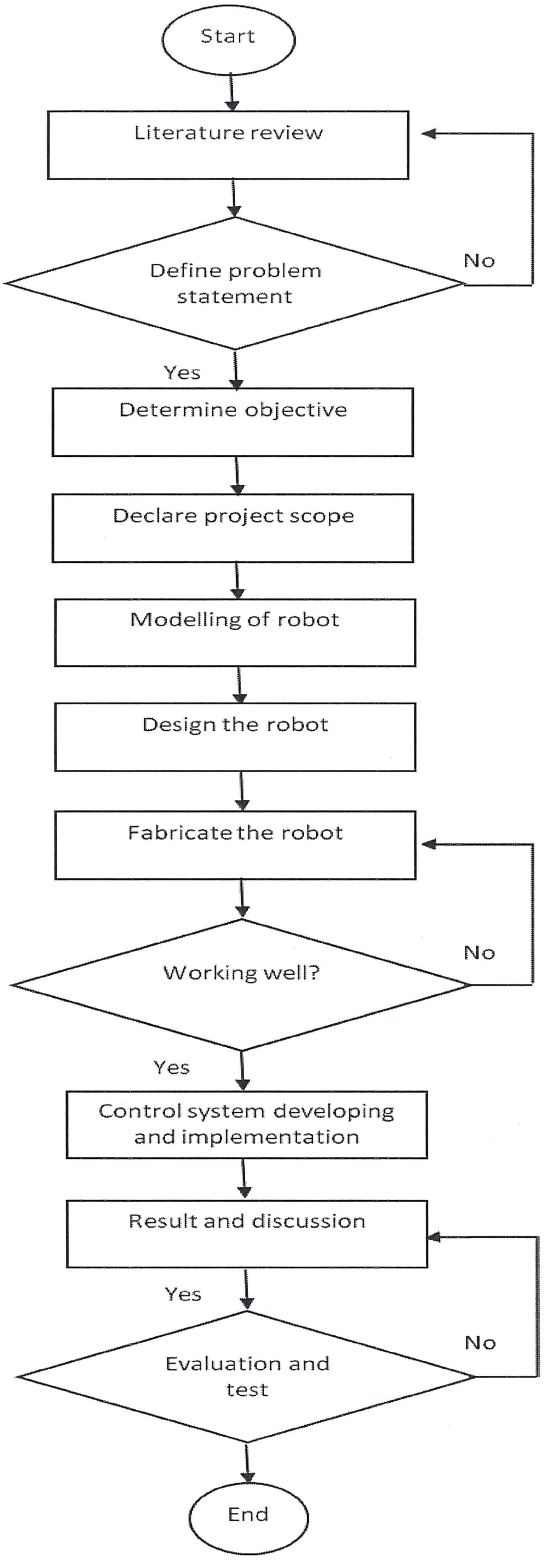


Figure 1.2 Project flow chart

1.6 Project Methodology

The project involves the following activities:

i. Literature review

Journal papers regarding to the topic was reviewed to investigate the problem and scope of the project. From the papers reviewed, there are many types of control of mobile robot. The mobile robot is controlled by AFC, PID and FLC controller to perform zero error tracking trajectory. Different type of controllers is use and the result is compared. Furthermore, the mobile robot is tested in simulation and also in real time experiment to perform in different types of trajectories, for example circular trajectory, straight line trajectory and parabola trajectory. The graph of the desired trajectory and actual trajectory are compared. Besides that, the journal papers also declare about the modelling and design of the mobile robot. There are different types of mobile robots use in the experiment, for example holonomic mobile robot and also non-honolomic mobile robot.

ii. Problem statement

After review the journal papers, some problems regarding to the control of mobile robot in restricted environment are list out. There are still have certain aspect did not cover in restricted environment, so some improvements still can be done to the project. The main problem of the project is the mobile robot show a big tracking error in its actual trajectory compared to the desired trajectory. Next problem is the efficiency of mobile robot. The problem statements are more focus in safety factor and efficiency of the mobile robot to complete a task. By analysing the problem, the project can be improved well.

iii. Research objective

To solve the problem statement, objectives must be determined. The first objective of the project is to control practically wheeled mobile robot in restricted environment with zero track error. Next objective is to fabricate three wheeled mobile robot and lastly is to apply the AFC controller algorithm with different types of restricted environments.

iv. Scope

Project scope is necessary to declare in the project so that the scope of the project can be minimized; otherwise it will take time to perform. The control of wheeled mobile robot is more focus in three wheeled mobile robot that consist of two differential wheels and one castor wheel. Furthermore, the mobile robot can sustain medium load and move smoothly low velocity of. Moreover, for the project, the mobile robot is only tested in circular and rectangular path.

v. Modelling of robot

The modelling of the robot in both kinematic and dynamic is explained in this section. The kinematic modelling of robot is study of motion of the mobile robot by ignoring the force and moment, while for dynamic modelling, it is focus on the force and moment in the motion of the wheeled mobile robot.

vi. Design and fabrication

The draft design of the wheeled mobile robot is shows. The robot is a non-holonomic mobile robot which consists of two differential wheels and one castor wheel. Furthermore, the types, quantity and price of the materials needed for fabrication is listed in the table 1.1.

Table 1.1 Bill of material of the project

No	Item	Price per unit (RM)	Quantity	Total price (RM)
1	Arduino mega	205.00	1	205.00
2	Pneumatic wheel with diameter (8 inches)	120.00	2	240.00
3	Aluminium sheets grade 6063 (1000x500x10mm)	700.00	3	2100.00
4	Aluminium profile grade 6063(20x20mm)	175.00	7m	1225.00
5	Brush DC motor (30.1)	618.40	2	1236.80
6	NP7-1 Lead Acid battery and charger	190.00	1	190.00
7	DC motor driver, MD30C	150.00	2	300.00
8	Bearing	11.00	2	22.00
9	Rotary Encoder C/W Coupling (500 PPR	263.40	2	526.80
10	Castor wheel	2.00	1	2.00
			Total :	RM 6047.6

vii. Control system developing and implementation

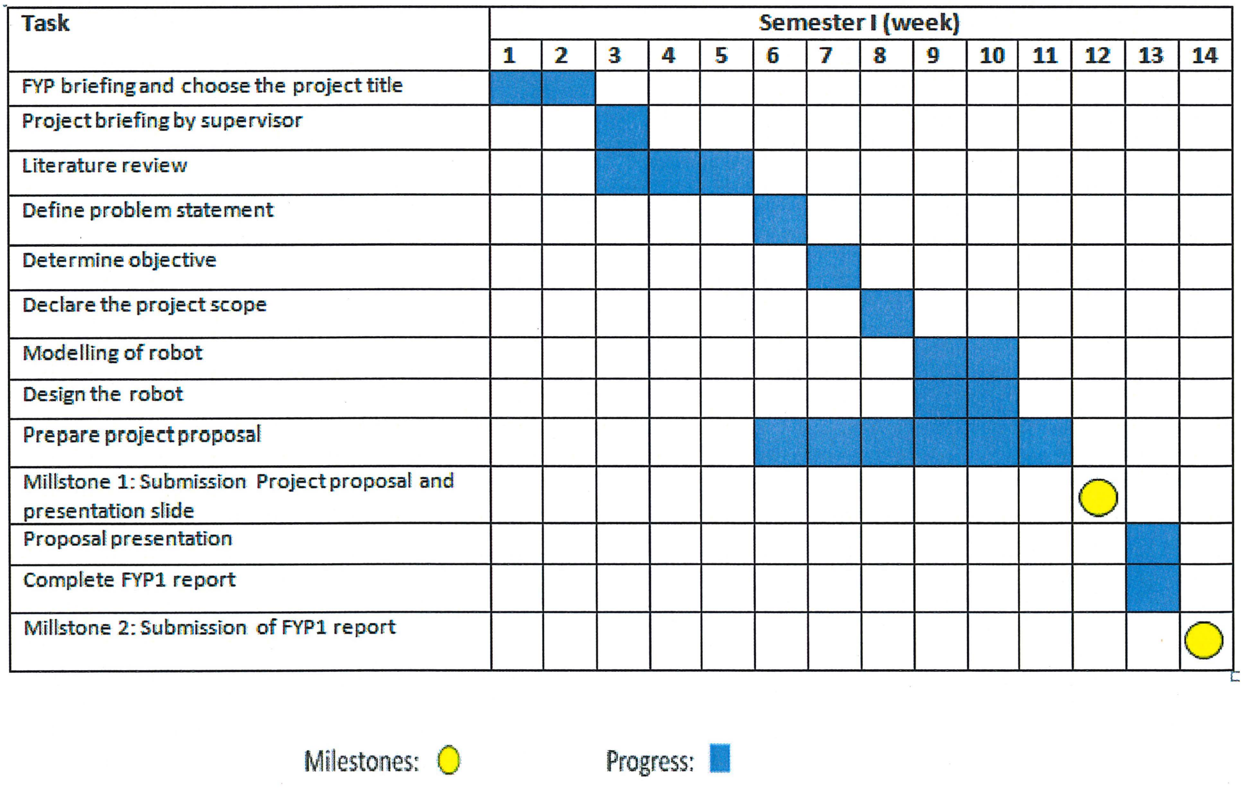
The control system will be implemented in the wheeled mobile robot. In this project, Active force control (AFC) with neural network is used to control the wheeled mobile robot to move in desired path. Besides, the PID controller will be used to compare with the AFC controller.

viii. Result, discussion and analysis

The desired and actual trajectory of the path control mobile robot will be compared in the graph. The discussion and analysis will be done according to the result. However, the error between the desired and actual trajectory should be in zero level.

1.7 Project Gantt chart

1.7.1 Project Gantt chart - Fyp1



Task	Semester I (week)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FYP briefing and choose the project title	🟦	🟦												
Project briefing by supervisor			🟦											
Literature review			🟦	🟦	🟦									
Define problem statement						🟦								
Determine objective							🟦							
Declare the project scope								🟦						
Modelling of robot									🟦	🟦				
Design the robot									🟦	🟦				
Prepare project proposal						🟦	🟦	🟦	🟦	🟦	🟦			
Millstone 1: Submission Project proposal and presentation slide												●		
Proposal presentation													🟦	
Complete FYP1 report													🟦	
Millstone 2: Submission of FYP1 report														●

Milestones: ● Progress: 🟦

1.7.2 Project Gantt chart -Fyp2

Task	Semester II (week)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fabricate the robot	🟦	🟦	🟦											
Test and troubleshooting			🟦	🟦										
Control system developing and implementation					🟦	🟦	🟦							
Test and troubleshooting							🟦	🟦						
Result, discussion and analysis									🟦	🟦	🟦			
Design poster												🟦		
Poster presentation													🟦	
Finalize the thesis													🟦	
Millstone3: Submission of thesis														🟡

Milestones: 🟡 Progress: 🟦

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is to provide a review of control of wheeled mobile robot in restricted environment from the existing literature such as journal and articles. The purpose of this chapter is to investigate the problem in control of wheeled mobile robot in restricted environment from the journal paper. Besides, literature review also provides a clear scope for this project. The review details included different types of wheel mobile robot, wheels and also controllers. This chapter will help to give better understanding toward control of mobile robot.

2.2 Wheeled Mobile Robot

Wheeled mobile robot is a type mobile robot that able to move within environments with the assistance of the wheel. Nowadays, wheel mobile robot is wide use in different application, especially in industry. This is not just replacing manpower, it also improve the work efficiency. Wheeled mobile robot is able to complete a complex task with information processing data coming from sensor using for artificial intelligence (Deng et al., 2014). There are several types of wheeled mobile robots, such as holonomic and non-holonomic mobile robot. Furthermore, size of wheel also should be considered. Frictional force will reduce if the width of the wheel is small. (Chavan & Minase, 2015)

2.3 Non-Holonomic Mobile Robot

Non-holonomic mobile robot is classified as mobile robot that moves with two degree of freedom. (Muniandy & Muthusamy, 2012) Moreover, according to Elyoussef, De Pieri, Moreno, & Jungers, (2012), most of the design of the non-holonomic wheel mobile robot consist of two simple perpendicular wheel and one castor wheel. Normally the non-holonomic wheel mobile robot is differential drive as mentioned by Murelitharan Muniandy and Kanesan Muthusamy (2012). Car with Ackerman driving is the best example for the non-holonomic vehicle. Shahmaleki, Mahzoon, & Shahmaleki (2009) had carried out an experiment on designing fuzzy logic controller by implementing on non-holonomic mobile robot as shown in Figure 2.1.The mobile robot cannot move sideward because it consist of differential wheel.

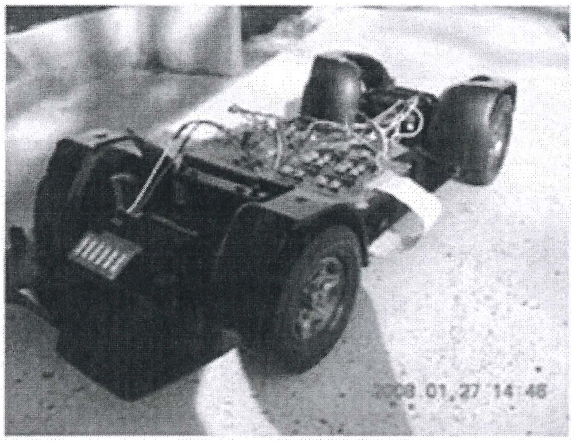


Figure 2.1 Non-holonomic wheel mobile robot
Source: (Shahmaleki, Mahzoon, & Shahmaleki, 2009)

Non-holonomic mobile robot is easy to control, and it can be moved forward and rotate in place (Leena & Saju, 2016). According to Murelitharan Muniandy and Kanesan Muthusamy (2012), most of the wheel mobile robots are differential drive as shown Figure 2.2. Differential wheel consists of two parallel wheels; both wheels are drive with independent actuators for each wheel. Some of the designs consist of a third wheel in the wheel mobile robot, which is castor wheel. Castor wheel is a non-drive wheel that can attached at the back to support the mobile robot (Leena & Saju, 2016). According to Chavan & Minase (2015), caster wheel is implemented in their mobile robot because it could reduce cost, energy consumption, and weight of the mobile robot.

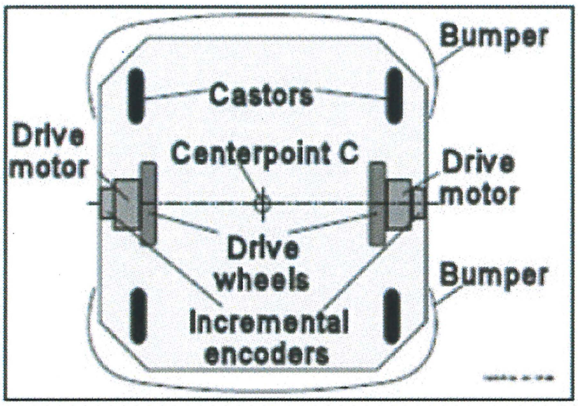


Figure 2.2 Construction details of the differential drive WMR
Source: (Muniandy & Muthusamy, 2012)

2.4 Holonomic Mobile Robot

Holonomic mobile robot is able to move diagonally. The position of the wheel will not change when the mobile robot is move around, however it can move forward, backward, left and right. The holonomic mobile robot has smaller turning radius compared to conventional vechicles. Furthermore, holonomic mobile robot only can perform better in flat and smooth surface (Kuzyk & Solana, 1973). Normally for holonomic mobile robot, it is omni-directional drive. Moreover, there are two type of Omni-directional drive mobile robot, which is Omni-directional drive mobile robot with Mecanum wheel as shown in Figure 2.3 and Omni-directional drive mobile robot with Synchronise-drives (Chavan & Minase, 2015). Furthermore, Hashemi, Ghaffari Jadidi, & Ghaffari Jadidi (2011) have used a four wheel Omni-directional mobile robot because it is more accurate and able to move in high speed.

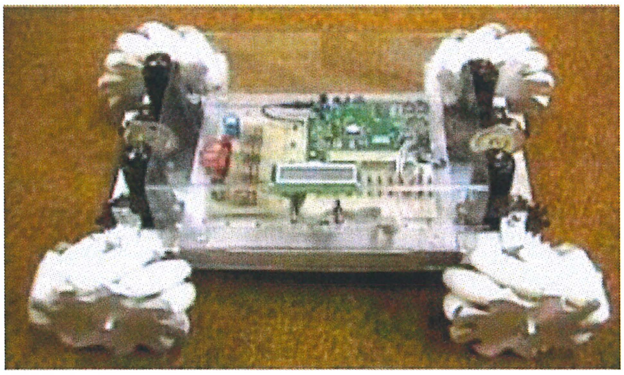


Figure 2.3 Holonomic mobile robot
Source: J.A.Cooney et. al (2004)

According to (Gfrerer, 2008), Mecanum wheel is a type of wheel that consists of roll aligned on the circumference of the wheel, as show in the figure 2.4, which was designed in Sweden. A mobile robot that consists of Mecanum wheel can perform omni-directional movement.

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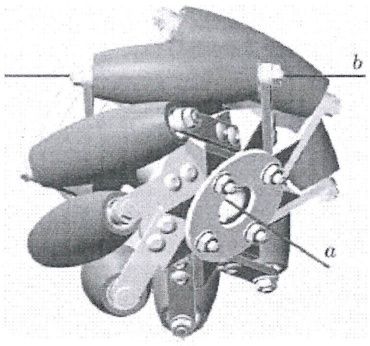


Figure 2.4 Mecanum wheel
Source: A.Gfrerer (2008)

The advantages and disadvantages of the holonomic and non-holonomic drive system are illustrated in table2.1. For this project, we will use in our wheeled mobile robot the non-holonomic drive with two differential wheels and one castor wheel.

Table 2.1 Advantages and disadvantages of holonomic and non-holonomic drive system wheel mobile robot

	Advantages	**Disadvantages**
Non-holonomic drive (with castor wheel)	• Easy to control • The mobile robot can rotate around true centre	• The mobile robot very hard to move from a flat surface to a slope
Holonomic drive	• The robot can turn easily	• Hard to control • Poor performance in rough surface

Source: (Chavan & Minase, 2015), (Gfrerer, 2008)

2.5 Wheeled Mobile Robot Controllers

There are many types of controllers to control the path of the mobile robot. It is always required an appropriate controller to control the mobile robot to move in accurate trajectory (Deng et al., 2014). From all journals reviewed, different types of controllers are implemented to the mobile robot to minimize the track errors of paths as shown in table 2.2. Different types of controllers are use in the experiment such as Proportional-Integral-Derivative (PID), Fuzzy logic control (FLC), Active force control (AFC).

Table 2.2 Types of controllers

Author	Year	Types of controllers	Result
MohammedA.H.Ali, Wan Azhar B. W. yussof, Zamzuri B.Hamedon, Zulkifli B. M. Yussof	2015	• PD • AFC • PD-AFC	• PD has big track error • AFC has small track error • PD-AFC track error is always in zero level
Ehsan Hashemi, Maani Ghaffari Jadidi, Navid Ghaffari Jadidi	2011	• PI-LQT • PI-fuzzy-LQT	PI–fuzzy-LQT controller present a better performance compared to the PI-LQT method.
Elie Maaloufa , Maarouf Saada , Hamadou Saliahb	2006	fuzzy logic controller (FLC)	Fuzzy logic controller enables the mobile robot move in the desired path with small tracking error and in appropriate speed.
Fernando Martín , Concepción A. Monje, Luis Moreno, Carlos Balaguer	2015	PID controller (fractional PID and traditional PID)	Fractional PID controller is more flexible compared to the traditional PID controller.

Cassius Z. Resende , Ricardo Carelli, Mário Sarcinelli-Filho	2013	A controller with fixed saturated and a controller with fuzzy gain	A controller with fuzzy gain gives a better result in the path tracking compared to a controller with fixed saturated. The controller with fuzzy gain able to perform path tracking with small error.

Ali, Yusoff, Hamedon, & Yusssof (2015) had control the motion of the wheeled mobile robot in the restricted environment by using PD, AFC, and PD-AFC controller in the MATLAB SIMULINK. The results of those three controllers were compared. By referring to the results, PD-AFC controller tracked error was always in zero level, while AFC controller and PD controller has small track error and big track error respectively. However, the PD-AFC controller was able to maintain the track error in zero level because the controller can eliminate the effect of disturbances.

Hashemi et al. (2011) had carried out an experiment to determine the rectangular trajectory following behaviour for different controller and velocity. In this experiment, PI-LQT controller and PI-fuzzy –LQT controllers were used and the results were compared. The PI-fuzzy controller has a better result compared to PI-LQT controller. The PI-fuzzy-LQT controller can controlled with external load disturbance with least error.

According to Maalouf, Saad, & Saliah (2006), a fuzzy logic controller can use for path tracking of a wheeled mobile robot. This experiment was carried out by testing the path tracking on SRI simulator and real robot. By referring to the result, both simulation and real time responses were approximate same. The fuzzy logic controller shows a good performance in path tracking, it able to move in the desired path with small error and in appropriate speed.

Martín, Monje, Moreno, & Balaguer (2015) had study about the PID controller. They carried out an experiment to control the position of DC motor in simulation and real by using fractional PID and traditional PID. From the experiment, fractional PID controller show a better result because it is more flexible, the cost function can be change for different control specification.

A controller with fixed saturated and a controller with fuzzy gain were used by Resende, Carelli, & Sarcinelli-Filho (2013) for unicycle-like robots to tracking a desired trajectory. The trajectories performed by both controllers were compared with the desired trajectory. However, the controller with fuzzy gain has better performance. The mobile robot with fuzzy gain controller was able to track a trajectory with small distance error. Moreover, it also can limit the velocity and control the signal of the robot to reduce the error

2.6 PID Controller

Proportional-Integral-Derivative (PID) controller had been use for many years to control applications in industry. It has simple design and good performance in control some process (Shah & Agashe, 2016). PID controller has output of proportional term response to the error, consider the past error by integral term and predict future error by derivative term (Astrom & Hagglund, 2011). The three parts in this controller can achieve and solve the control problems; Integral has slow response to the error, while the proportional has fast response to the error but cannot achieve the desired result and the derivative accelerate the system to reach desired value (Shinskey, 2006).

2.7 Fuzzy Logic Control

Fuzzy logic control (FLC) is a control process that gives an output from an input. Fuzzy logic is not just true or false, it uses a continuous range of truth values in the interval [0, 1], which is focus on the truth condition (Karnik & Mendel, 1998) FLC has three basic operations, which are fuzzification, Membership function, rules & inference and defuzzification. Implementation of FLC will enable flexible control behaviour. In fuzzification stage, it changes the input crisp value to non crisp value. After fuzzification, the remaining is to defuzzify, which is to produce a non-fuzzy control action (Han, 2009).

2.8 Active Force Control

Active force control (AFC) is a control technique that establish by Hewit and Burdess 1981. AFC mostly work on measured and evaluated parameters to reduce the computation burden (Mailah & Priyandoko, 2010). Normally, AFC is use to control a dynamic system to make sure that the system is robust and stable when there are known and unknown disturbance. Furthermore, the AFC is simple, and effective in comparison with other controllers (Mailah & Priyandoko, 2007).

The comparison between the PID, FLC and AFC are depicted in table 2.3.

Table 2.3 Advantages and disadvantages of PID, FCL and AFC

Types of controller	**Advantages**	**Disadvantages**
PID	• Simple design • Have good characteristic in time domain • Robustness	• Only has three parameter • Cannot apply on system with fast change parameter
FLC	• Flexible • Has many parameters • Can deal with non-linear system	• Do not have good characteristic in time domain
AFC	• Simple, robust, effective • Able to make the dynamic system stable and robust	• Approach to the true parameter is slow

Sources: (Godjevac, 2005), (Meon, Mohamed, Ramli, Mohamed, & Manan, 2012)

2.3.1 PD-AFC

PD controller uses two control gains, which is Kp and Kd (Fang, Lin, & Wang, 2012). The derivative is able to investigate the future error or the system, so it can make the system stable. In other words, the derivative is designed to be proportional to the change of the output variable to avoid the sudden changes in control output (Temel, Yağli, & Gören, 2012). According to the Meon et al., (2012), the PD-AFC consist of two loops, the first loop consist PD controller while the second loop consist of AFC controller. Furthermore, Ali, Yusoff, Hamedon, & Yusssof (2015) had control the motion of the wheeled mobile robot in the restricted environment by using PD-AFC controller. The PD is operated based on kinematic parameter while AFC is operated based on dynamic parameter.

2.9 MATLAB-SIMULINK

MATLAB Simulink can be use for all types of dynamic system. The wheel mobile robot is controlled by controller such as PID, AFC, and FLC. The controller can be implemented with the robot system by using Simulink. Rao (2014) had carried out an experiment by using PID controller in MATLAB Simulink. Simulink is an adaptable interface which can implement different types of controller with a system. A simple Simulik model is as show in the figure 2.5. in some cases, the Simulink diagram can be accomplished by generating code (Huq, Lacheray, Fulford, Wight, & Apkarian, 2009) .

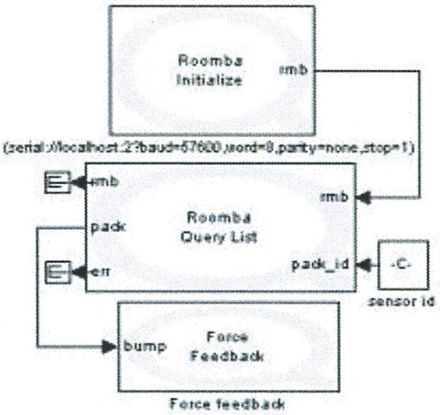


Figure 2.5 Simulink model
Source: (Huq et al., 2009)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains the methods that have been used to control the wheel mobile robot. The kinematic and dynamic modelling of the mobile robot will be explained in this section. Besides, the design of the wheel mobile robot and the controller are included in this section.

3.2 Modelling of Robot

Figure 3.1 shows the schematic diagram of wheel mobile robot. The mobile robot comprises three wheels driving system with two differential drive and one castor wheels. r is the radius of the wheel and L is the distance between the wheels of mobile robot.

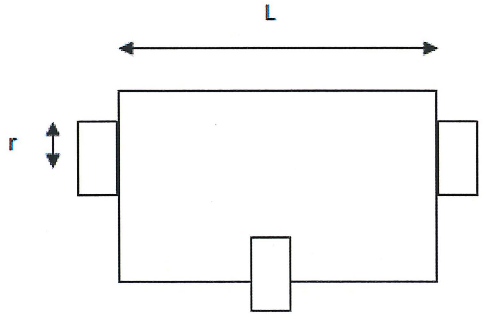


Figure 3.1 Schematic diagram of wheel mobile robot

Figure 3.2 show the motion of the mobile robot. The motion of the mobile robot can be described in global and local coordinate system.

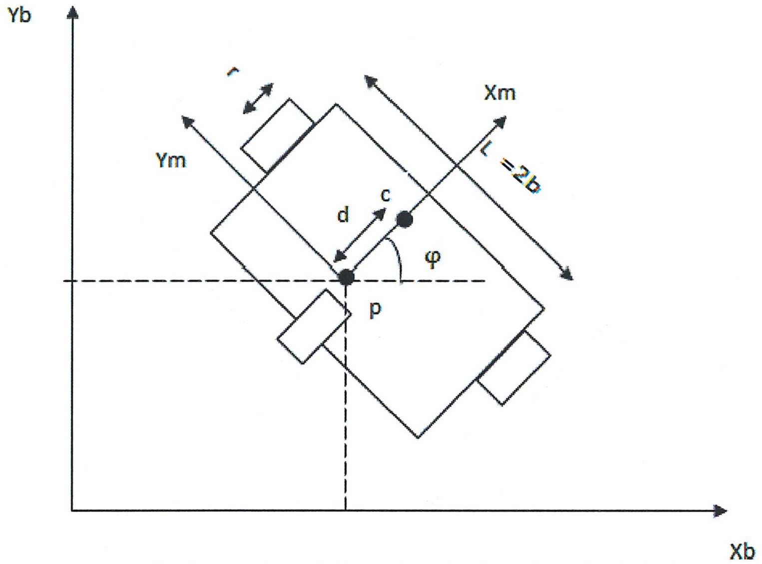


Figure 3.2 Motion of wheeled mobile robot in local and global coordinate system

3.2.1 Kinematic Modelling

Wheel linear velocity is given by:

$$v = rw \tag{3.1}$$

Wheel angular velocity is given by:

$$w = \frac{d\theta}{dt} \tag{3.2}$$

The mobile robot is moved with two differential drive wheels and a castor wheel, so the velocity is:

$$v = \frac{V_R + V_L}{2} \tag{3.3}$$

$$= \frac{r(W_R+W_L)}{2}$$

$$= \frac{r\dot{\theta}_R+r\dot{\theta}_L}{2}$$

$$= \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix}$$

The velocity of heading angle is given by:

$$\dot{\varphi} = \frac{V_R-V_L}{2b} \qquad (3.4)$$

The difference between angular velocity of right and left wheels can be illustrated as in Equation (3.5).

$$\dot{\varphi} = \frac{V_R-V_L}{2b} \qquad (3.5)$$

$$= \frac{r(W_R-W_L)}{2b}$$

$$= \frac{r\dot{\theta}_R-r\dot{\theta}_L}{2b}$$

$$= \begin{bmatrix} \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix}$$

The local coordinate system is show in Equation (3.6)

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos\varphi & -d\sin\varphi \\ \sin\varphi & d\cos\varphi \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \dot{\varphi} \end{bmatrix} \qquad (3.6)$$

The Equation (3.6) thus can be written in the term of angular velocity $\dot{\theta}_R$ and $\dot{\theta}_L$ as show in equation (3.7).

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\varphi - \frac{dr}{2b}\sin\varphi & \frac{r}{2}\cos\varphi + \frac{dr}{2b}\sin\varphi \\ \frac{r}{2}\sin\varphi - \frac{dr}{2b}\cos\varphi & \frac{r}{2}\sin\varphi - \frac{dr}{2b}\cos\varphi \\ \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \qquad (3.7)$$

3.2.2 Dynamic Modelling

The dynamic of the mobile robot can be derived using Lagrange equation as show in Equation (3.8).

$$\frac{d}{dt}\left(\frac{\delta k}{\delta \dot{q}}\right) - \frac{\delta k}{\delta q} = \tau_i - A^T(q)\lambda \qquad (3.8)$$

Where; k = kinetic energy

q = coordinate system

τ_i = exerted torque on the robot

$A^T(q)$ = constraints of robot

The kinetic energy of the mobile robot can be formulated as follows.

The kinetic energy of the robot body can be written as Equation (3.9):

$$KE_{body} = \frac{1}{2}m_r(\dot{x}^2 + \dot{y}^2) + \frac{1}{2}I_r\dot{\varphi}^2 \qquad (3.9)$$

The kinetic energy of the right wheel can be written as in Equation (3.10):

$$\begin{aligned} KE_{RW} &= \frac{1}{2}m_w(\dot{x} + b\dot{\varphi}\cos\varphi + d\dot{\varphi}\sin\varphi)^2 \\ &+ \frac{1}{2}m_w(\dot{y} + b\dot{\varphi}\sin\varphi - d\dot{\varphi}\cos\varphi)^2 + \frac{1}{2}I_w\dot{\varphi}^2 + \frac{1}{2}I_w{\theta_R}^2 \end{aligned} \tag{3.10}$$

And the kinetic energy of the left wheel can be written as in Equation (3.11):

$$\begin{aligned} KE_{LW} &= \frac{1}{2}m_w(\dot{x} - b\dot{\varphi}\cos\varphi + d\dot{\varphi}\sin\varphi)^2 \\ &+ \frac{1}{2}m_w(\dot{y} - b\dot{\varphi}\sin\varphi - d\dot{\varphi}\cos\varphi)^2 + \frac{1}{2}I_w\dot{\varphi}^2 + \frac{1}{2}I_w{\theta_L}^2 \end{aligned} \tag{3.11}$$

Thus, the total kinetic energy can be written as in Equation (3.12):

$$KE_{total} = KE_{body} + KE_{RW} + KE_{LW}$$

$$\begin{aligned} KE_{total} &= \frac{1}{2}m_r\dot{x}^2 + \frac{1}{2}m_r\dot{y}^2 + \frac{1}{2}I_r\dot{\varphi}^2 + m_w\dot{x}^2 + 2m_w\dot{x}d\dot{\varphi}\sin\varphi + m_wb^2\varphi^2 \\ &+ m_wd^2\varphi^2 + m_wy^2 - 2m_w\dot{y}d\dot{\varphi}\cos\varphi + I_w\varphi^2 + \frac{1}{2}I_w{\dot{\theta}_L}^2 \\ &+ \frac{1}{2}I_w{\dot{\theta}_R}^2 \end{aligned} \tag{3.12}$$

Since L=KE$_{\mathrm{total}}$,

Differential with respect to ẋ and x can be written as:

$$\frac{\delta L}{\delta \dot{x}} = m_r\dot{x} + 2m_w\dot{x} + 2m_w d\dot{\varphi}\sin\varphi \tag{3.13}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{x}}\right) = m_r\ddot{x} + 2m_w\ddot{x} + 2m_w d\dot{\varphi}^2\cos\varphi + 2m_w d\ddot{\varphi}\sin\varphi \tag{3.14}$$

$$\frac{\delta L}{\delta x} = 0 \tag{3.15}$$

From Equation (3.13)-(3.15), can be written as in Equation (3.16)

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{x}}\right) - \frac{\delta L}{\delta x} = m_r\ddot{x} + 2m_w\ddot{x} + 2m_w d\dot{\varphi}^2\cos\varphi + 2m_w d\ddot{\varphi}\sin\varphi \tag{3.16}$$

Differential with respect to ẏ and y can be written as:

$$\frac{\delta L}{\delta \dot{y}} = m_r\dot{y} + 2m_w\dot{y} - 2m_w d\dot{\varphi}\cos\varphi \tag{3.17}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{y}}\right) = m_r\ddot{y} + 2m_w\ddot{y} + 2m_w d\dot{\varphi}^2\sin\varphi - 2m_w d\ddot{\varphi}\cos\varphi \tag{3.18}$$

$$\frac{\delta L}{\delta y} = 0 \tag{3.19}$$

From Equation (3.17)-(3.19), can be written as in Equation (3.20)

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{y}}\right) - \frac{\delta L}{\delta y} = m_r\ddot{y} + 2m_w\ddot{y} + 2m_w d\dot{\varphi}^2\sin\varphi - 2m_w d\ddot{\varphi}\cos\varphi \tag{3.20}$$

Differential with respect to $\dot{\varphi}$ and φ can be written as:

$$\frac{\delta L}{\delta \dot{\varphi}} = I_r\dot{\varphi} + 2m_w\dot{x}d\sin\varphi + 2m_w b^2\dot{\varphi} + 2m_w d^2\dot{\varphi} - 2m_w\dot{y}d\cos\varphi + 2I_w\dot{\varphi} \tag{3.21}$$

$$\begin{aligned}\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\varphi}}\right) = {} & I_r\ddot{\varphi} + 2m_w\ddot{x}d\sin\varphi + 2m_w\dot{x}\dot{\varphi}^2\cos\varphi + 2m_w b^2\ddot{\varphi} + 2m_w d^2\ddot{\varphi} - \\ & 2m_w\ddot{y}d\cos\varphi + 2m_w\dot{y}d\sin\varphi + 2I_w\ddot{\varphi}\end{aligned} \tag{3.22}$$

$$\frac{\delta L}{\delta \varphi} = 2m_w\dot{x}d\dot{\varphi}\cos\varphi + 2m_w\dot{y}d\dot{\varphi}\sin\varphi \tag{3.23}$$

From Equation (3.21)-(3.23), can be written as in Equation (3.24)

$$\begin{aligned}\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\varphi}}\right) - \frac{\delta L}{\delta \varphi} = {} & I_r\ddot{\varphi} + 2m_w\ddot{x}d\sin\varphi + 2m_w\dot{x}\dot{\varphi}^2\cos\varphi + 2m_w b^2\ddot{\varphi} \\ & +2m_w d^2\ddot{\varphi} - 2m_w\ddot{y}d\cos\varphi + 2m_w\dot{y}d\sin\varphi + 2I_w\ddot{\varphi} \\ & -2m_w\dot{x}d\dot{\varphi}\cos\varphi - 2m_w\dot{y}d\dot{\varphi}\sin\varphi\end{aligned} \tag{3.24}$$

The constraints of robot movements are illustrated in Equations (3.25-29)

$$m\ddot{x} - md\ddot{\varphi}\sin\varphi - md\dot{\varphi}^2\cos\varphi = C1 \tag{3.25}$$

$$m\ddot{y} - md\ddot{\varphi}\cos\varphi - md\dot{\varphi}^2\sin\varphi = C2 \tag{3.26}$$

$$I\ddot{\varphi} - md\ddot{x}\sin\varphi + md\ddot{y}\cos\varphi = C3 \tag{3.27}$$

$$I_w\ddot{\theta}_R = \tau_R + C4 \tag{3.28}$$

$$I_w\ddot{\theta}_L = \tau_L + C5 \tag{3.29}$$

(C1, C2, C3, C4, C5) are coefficients related to the kinematic constraints.

$$A^T(q) = \begin{bmatrix} C1 \\ C2 \\ C3 \\ C4 \\ C5 \end{bmatrix} \qquad (3.30)$$

The equations (3.16), (3.20), (3.24) can be represented in general form of Lagrange Equation (3.31):

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} = B(q)r - A^T(q)^{\lambda} \qquad (3.31)$$

Where:

$$M(q) = \begin{bmatrix} m & 0 & 2m_w d\sin\varphi & 0 & 0 \\ 0 & m & -2m_w d\cos\varphi & 0 & 0 \\ 2m_w d\sin\varphi & -2m_w d\cos\varphi & I & 0 & 0 \\ 0 & 0 & 0 & I_w & 0 \\ 0 & 0 & 0 & 0 & I_w \end{bmatrix}$$

$$V(q,\dot{q}) \begin{bmatrix} 2m_w d\dot{\varphi}^2\cos\varphi \\ 2m_w d\dot{\varphi}^2\sin\varphi \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \qquad B(q)r = \begin{bmatrix} \tau_R & 0 \\ 0 & \tau_L \end{bmatrix}$$

$A^T(q)$ =Transpose of the onstraints equation

m: Total mass of Mobile Robot = *mr* + 2*mw*

mr: The mass of the platform without the driving wheels and DC motors

mw: The mass of the driving wheels and the DC motors.

I: total moment of inertia of mobile robot = *Ir* + 2*mw* ($d^2 + b^2$) + 2*Iw*

Ir : The moment of inertia of the body of robot without the driving wheels and the motors about axis passed through *P*.

Iw : the moment of inertia of each wheel and the motor rotor about the wheel axis.

τ_r : The torque exerted on wheel axis by right motor.

τ_l : The torque exerted on wheel axis by left motor.

λ: The Lagrange multiplier coefficient.

3.3 Design of Wheeled Mobile Robot

This is a primary design for the wheeled mobile robot. Figure 3.3 and 3.4 show the 3D view and Orthographic view of the first draft design of wheeled mobile robot.

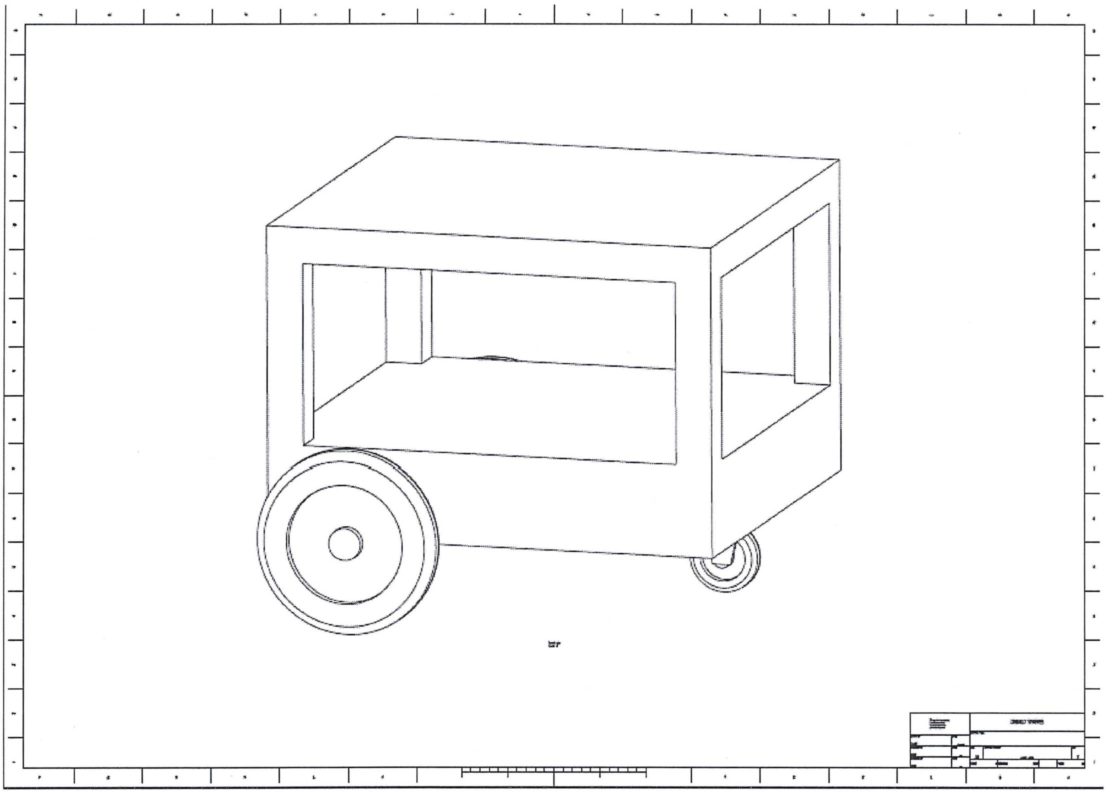


Figure 3.3 3D view of the first design of wheeled mobile robot

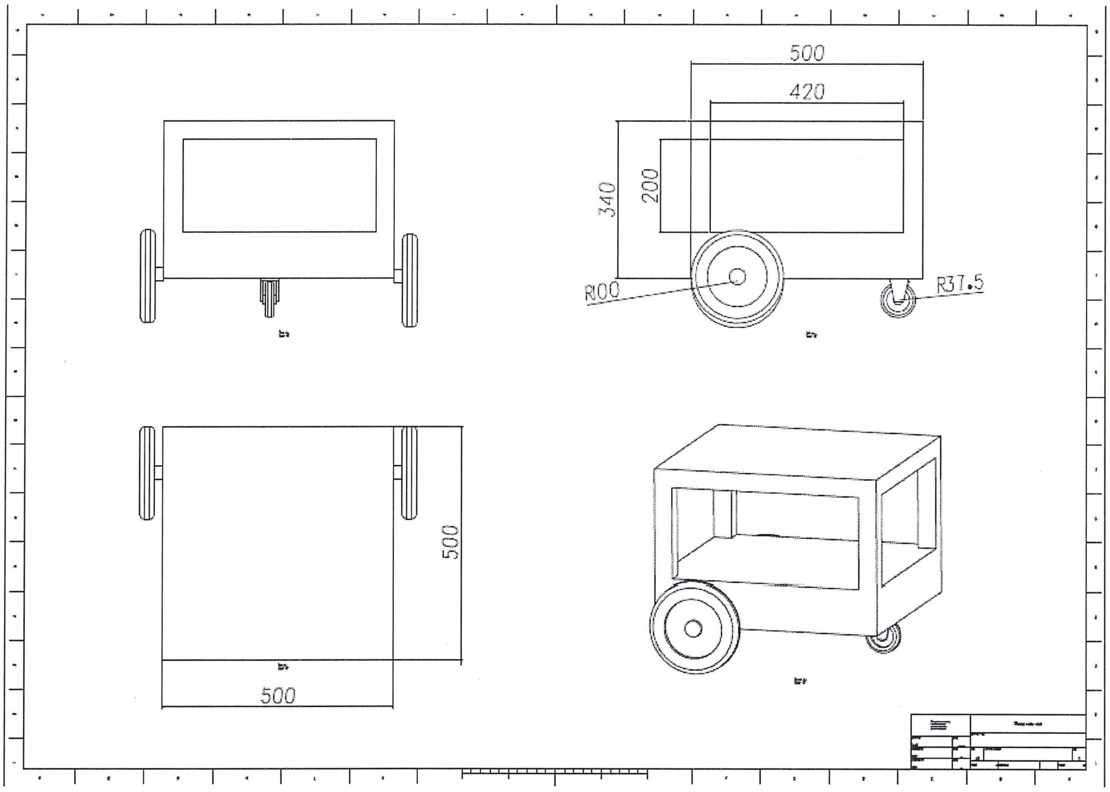


Figure 3.4 Orthographic view of the first design of wheeled mobile robot

The final design of the mobile robot is shows in figure 3.5. Figure 3.6 shows the Orthographic view of the wheeled mobile robot. The wheeled mobile robot is non-holonomic mobile robot, which consists of two differential wheels and one castor wheel. The length, width and height of the wheeled mobile robot is 900mm x 600mm x 350mm. The diameter of the differential wheel is 200mm, while the diameter for castor wheel is 80mm. Furthermore, the body of the wheeled mobile robot is made of aluminium plate and aluminium profiles.

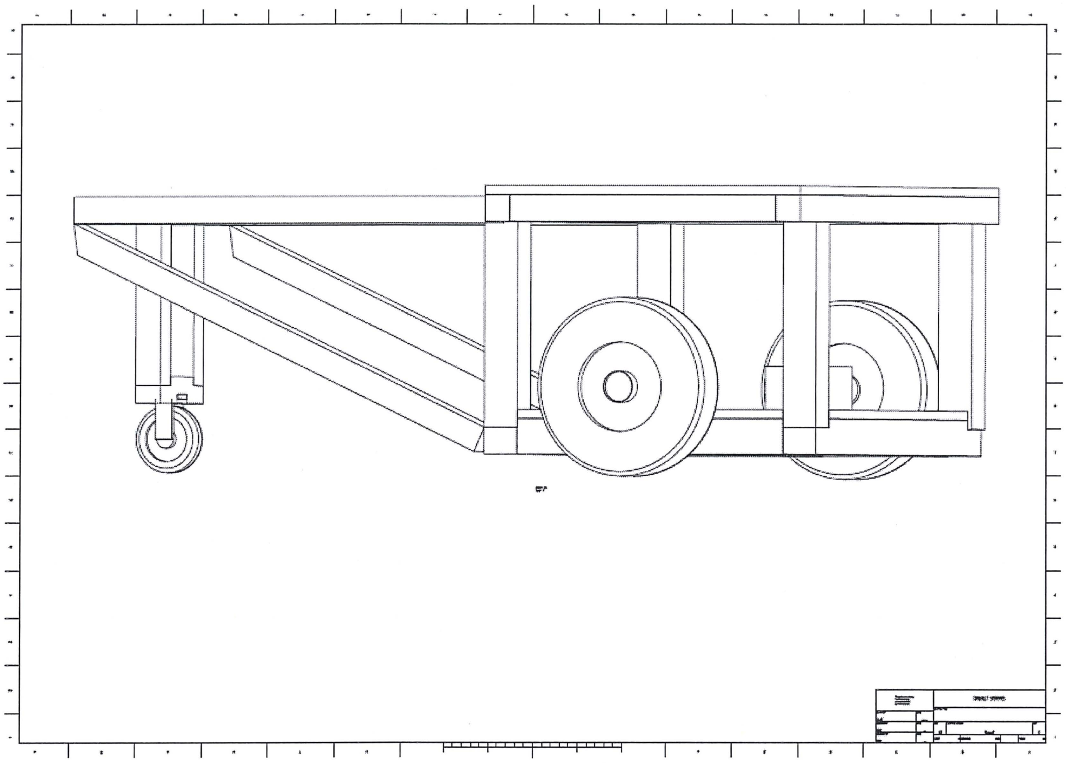


Figure 3.5 3D view of the wheeled mobile robot

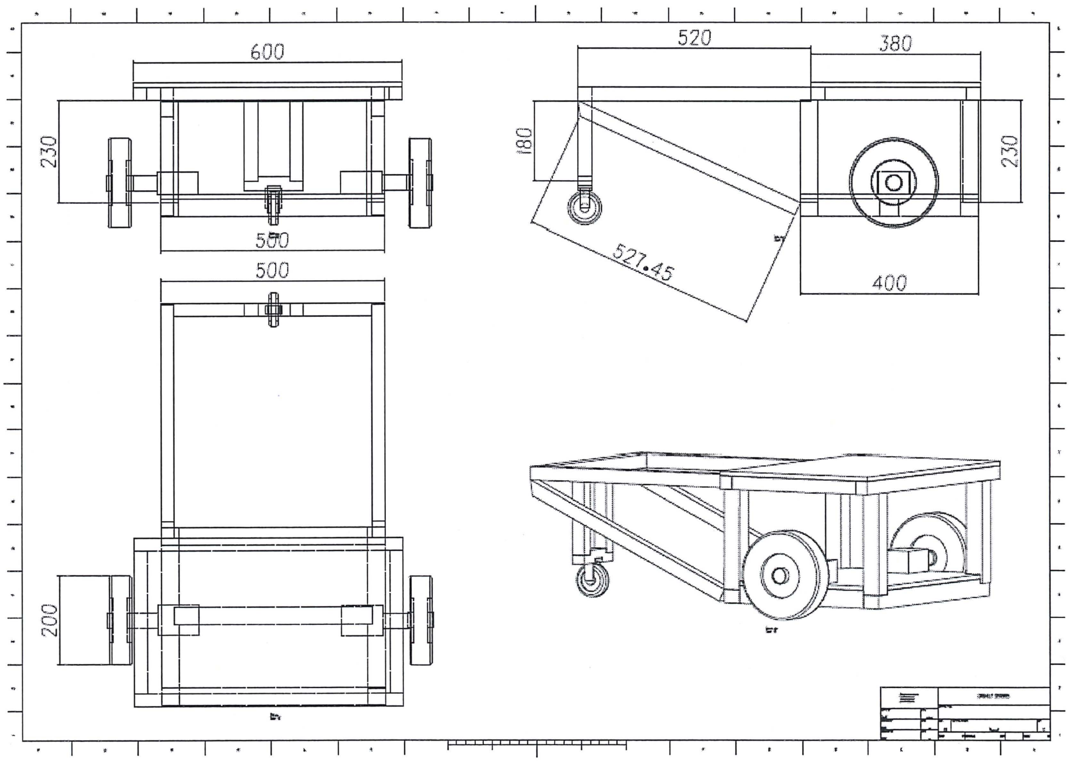


Figure 3.6 Orthographic view of the wheeled mobile robot

3.4 Mechanical Part Fabrication

In this topic, the explanation on how the mechanical construction of the wheeled mobile robot from concept and idea to completion will be discusses. The body part of the robot, materials, and fabrication process are shows in the section below.

A 900mm x 600mm x 350 mm wheeled mobile robot is fabricated as shows in the figure 3.7. Each part of the wheeled mobile robot is labelled.

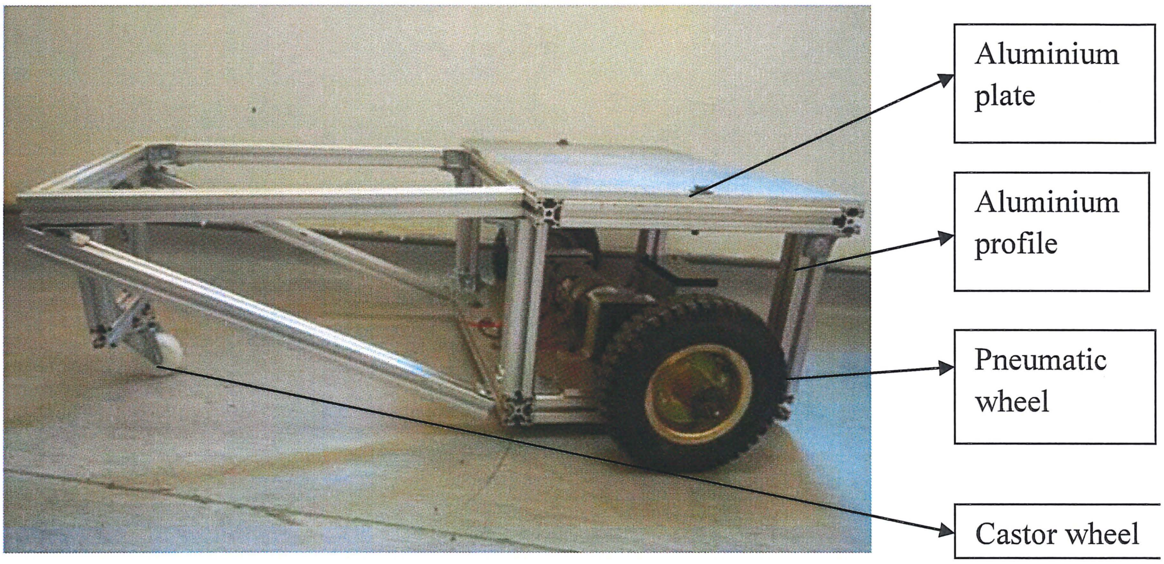


Figure 3.7 The wheeled mobile robot

3.4.1 Aluminium Profile

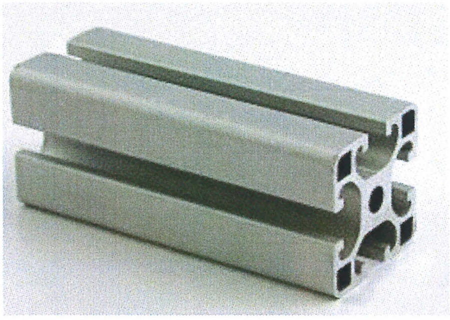


Figure 3.8 Aluminium profile
Source: e-Bay

The body structure of the mobile robot is made of 30x30mm and 40x40 aluminium profile. The base of the mobile robot is made of 40x40 aluminium profile for a stronger base support, while the upper part body of the mobile robot is made of 30x30 aluminium profile. The aluminium profiles are cut to desired lengths and after that it is assembled by using the L- bracket, bolt and nuts.

3.4.2 Aluminium Plate

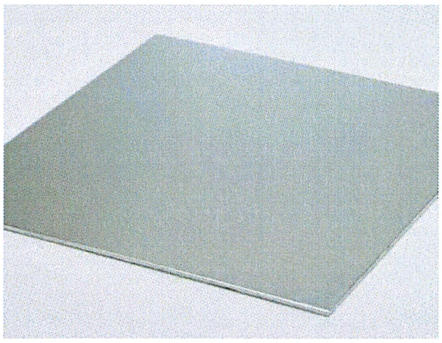


Figure 3.9: Aluminium plate
Source: e-Bay

10mm thick aluminium plate is use as the cases of the mobile robot. The aluminium plates are cut into 400x500mm and 600x380mm respectively to cover the body of the mobile robot. The 10mm aluminium plate is chosen because it is heavy enough to let the mobile robot move in stable condition. Besides, the aluminium plate also can cover the electrical component such as battery, motor, and controller of the mobile robot. It can protect the core of the mobile robot.

3.4.3 Motor Shaft and Bearing

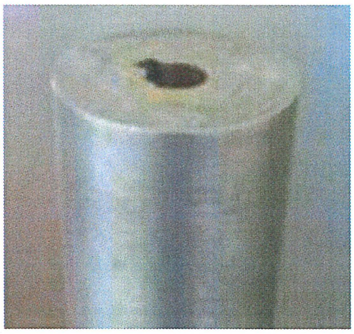


Figure 3.10 Motor shafts with key hole

Figure 3.11 Bearing
Sources: Lelong

The motor shaft with key hole as show in figure 3.10 is made of mild steel. The motor shaft with key hole is made to connect the motor with the wheel. key hole of the motor shaft is made by the Die-sink Electric Discharges (ED) Machine. This machine is able to produce relatively sharp internal corners and deep narrow shapes with drafted walls. In addition, the ED machining is the only method for hardened steels. While for the bearing as show in figure 3.11, it is installed on the motor shaft is to support the body of the mobile robot with its wheels. The 40mm bearing is chosen and is installed on the both motor shafts. The motor shafts and the wheel are connected by welding process as show in figure 3.12.

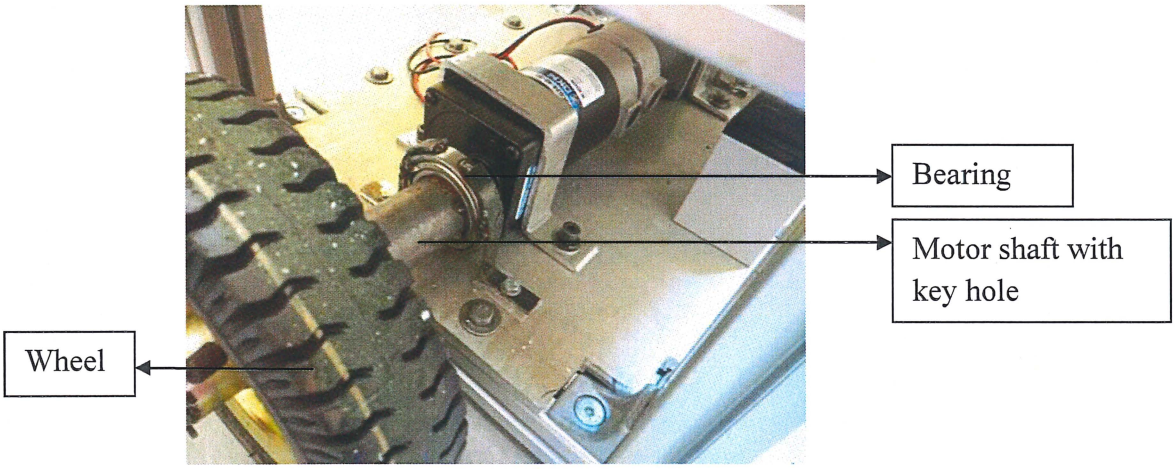


Figure 3.12 Wheel installed with the shaft and bearing

The process of fabrication has been decided after finished the dimensioning of each part and choosing the materials. The table below shows the parts, the material and the manufacturing process used for fabricated the mobile robot.

Table 3.1 The parts, material and manufacturing process used

No.	Parts	Material	Process
1	Body support	Aluminium	Sawing & Drilling
2	Body casing	Aluminium	Sawing & Drilling
3	Motor shaft	Mild steel	Turning, Drilling, Electric Discharges & Welding

3.5 Electrical and Electronic Part

This part is to provide the details of the electrical and electronic of the wheel mobile robot. All the components used are listed and clearly explained in term of their function. Besides, the schematic diagram and the real circuit are show below.

3.5.1 Motor Driver, MD30C

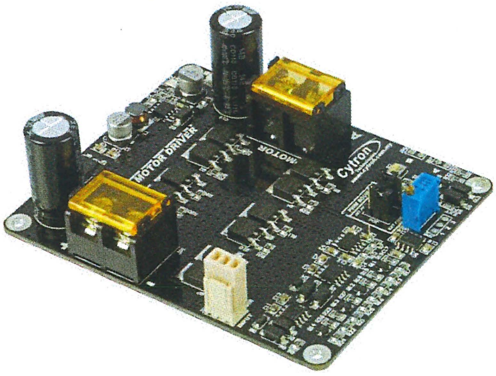


Figure 3.13 MD30C
Source: Crytron

MD30C is a motor driver that able to drive high power DC motor up to 80Apeak and 30A continuously, so for the project, the motor driver, MD30C as show in the figure 3.13 is use to control the speed and direction of the mobile robot.

3.5.2 Dc Brush Motor with Gearbox 30:1

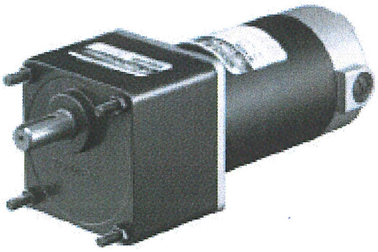


Figure 3.14 DC brush motor with gearbox 30:1
Source: Cytron

DC brush motor has a big starting torque and excellent mobility. The DC motor with model 8DCG24-40-30 has output power of 40W, and rated torque 39.77kg.cm, which is able to move in high torque condition. The DC brush motor is comprised of gearbox with gear ratio of 30:1 in order to slow down the speed of the motor to a ratio of 30.

3.5.3 Rotary Encoder

Figure 3.15 Rotary encoder
Source: Cytron

The rotary encoder is to measure the torque and acceleration of the wheel mobile robot. The torque and the acceleration measure by the rotary encoder is the actual torque and actual acceleration, which will compared it with the desired torque and desired acceleration in the MATLAB.

3.5.4 Electrical Circuit Design

The core chip set of this project is Arduino Mega; it is the main controller of this project. A motor driver, MD30C is used to control the brush DC motors with gear box 30:1. For the rotary encoder, it is use to measure the torque and the acceleration of the mobile robot. The figure 3.16 shows the electrical circuit design of the system. The motors are supplied by 12 V and for the encoder, it is supplied by 5V.

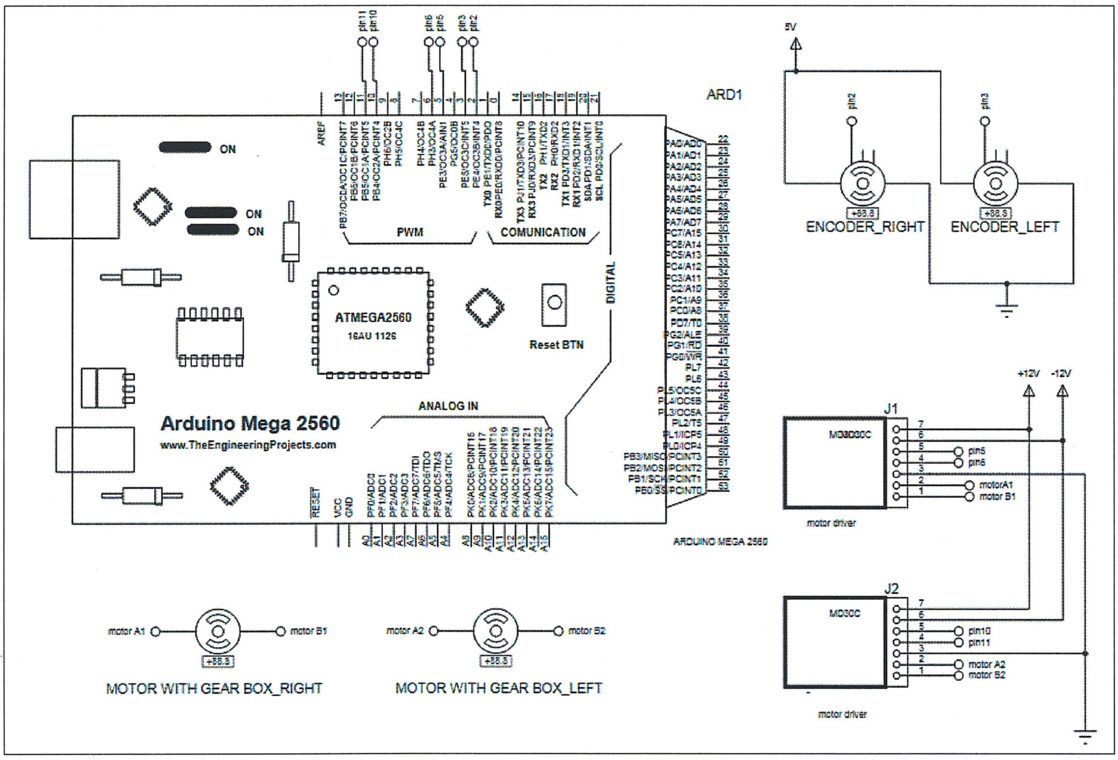


Figure 3.16 Circuit design of the system

3.6 Software Development

In section, it will provide the details of the soft ware development of this project. The design of the controller in Simulink, PD controller, design of fuzzy logic controller and interface arduino with the Simulink to control the actual mobile robot in the specific trajectories will be discussed with details in this section.

3.6.1 Design of Controller

This is the controller design of path control mobile robot which is controlled by combination of Proportional-derivative (PD) and Active force control (ACF) controller, which is PD-AFC. Figure 3.17 shows the design of PD-AFC implemented in the control of wheeled mobile robot.

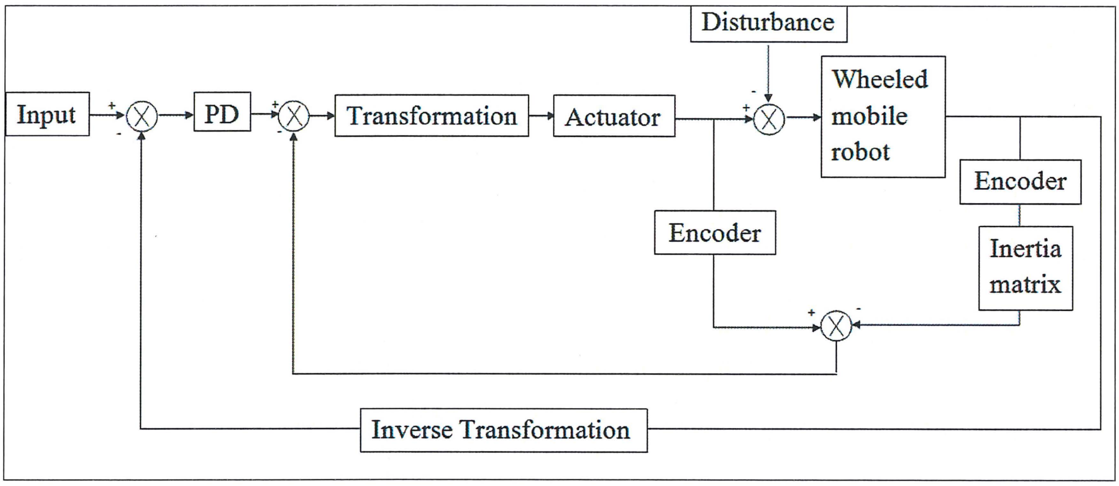


Figure 3.17 PD-AFC scheme

The control loop consists of two loops, namely outer loop and inner loop. PD controller is in the outer loop of the control loop. It is operate based on kinematic parameters. This controller is used as reference acceleration for AFC.

The inner loop of the control loop is AFC control strategy, which is able to make the dynamic system stable and robust. The AFC is depending on the angular acceleration of the wheel and inertia matrix. Furthermore, AFC with fuzzy logic controller will be implemented to the system to estimate the inertia matrix. The acceleration with inertia matrix will be compared with the torque to estimate the torque disturbance.

3.6.2 Proportional Derivative (PD) Controller

The PD controller is used to implemented reduce the error of the control trajectory. The PD controller is used as references acceleration for the active force controller strategy to estimate the torque. The equation (3.32)-(3.34) are the design of the PD controller.

$$\dot{x}_{error} = (\dot{x}_{ref} - \dot{x}_{act})[k_p] + [k_d][\frac{d_{\dot{x}_{ref}-\dot{x}_{act}}}{d_t}] \tag{3.32}$$

$$\dot{y}_{error} = (\dot{y}_{ref} - \dot{y}_{act})[k_p] + [k_d][\frac{d_{\dot{y}_{ref}-\dot{y}_{act}}}{d_t}] \tag{3.33}$$

$$\dot{\varphi}_{error} = (\dot{\varphi}_{ref} - \dot{\varphi}_{act})[k_p] + [k_d][\frac{d_{\dot{\varphi}_{ref}-\dot{\varphi}_{act}}}{d_t}] \tag{3.34}$$

3.6.3 Active Force Control (AFC)

The AFC control is implemented in the inner loop of the control system. It is depending on the angular acceleration of the wheel and Inertia Matrix (IN). The IN is estimated by using the fuzzy logic controller. The fuzzy system consists of one input and two outputs. The fuzzy set variables are shows in the table 3.2. The input of the fuzzy logic system is φ, and the outputs are IN right and IN left. The fuzzy rules and the degree membership of the input and output are created as shows in the table 3.2 and figure 3.18.

Table 3.2 Fuzzy set variables for the input and outputs

	Fuzzy set variables	
Input	Heading rotation , φ	{Very Low, Low, Medium, High, Very High}
Output	IN for right wheels, IN_R	{Very Small, Small, Medium, Large, Very Large}
	IN for left wheels, IN_L	{Very Small, Small, Medium, Large, Very Large}

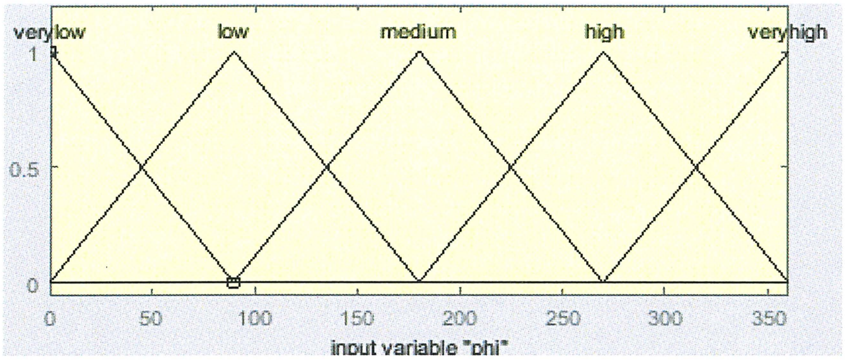


Figure 3.18 (a): Degree membership of input, φ

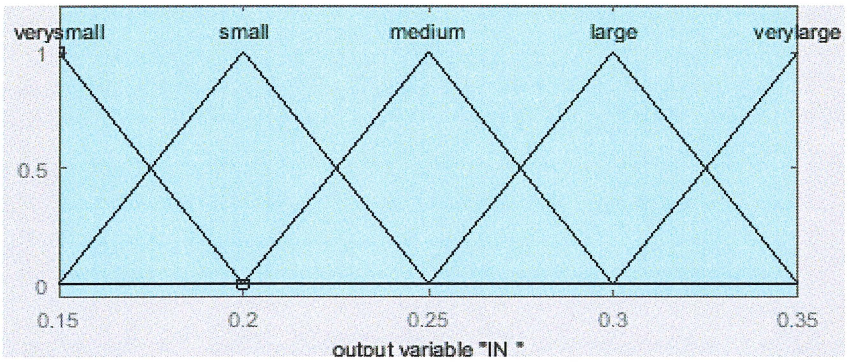


Figure 3.18 (b): Degree membership of output, IN_R

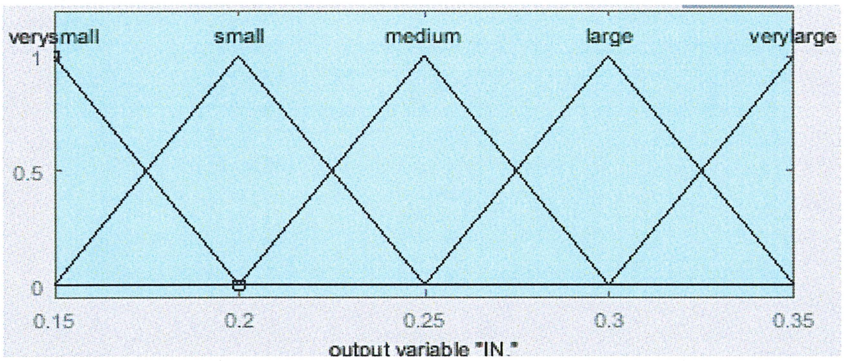


Figure 3.18 (c): Degree membership of output, IN_L

The torque of the system can be calculated from the equation (3.35). The applied torque and actual torque are determined by multiply the angular acceleration and the Inertia Matrix.

$$T = I.\ddot{\theta} \qquad (3.35)$$

Where, T= Torque

I = Inertia Matrix

$\ddot{\theta}$ = Angular acceleration

3.6.4 Control Loop

Figure 3.19 shows the control loop of the system, the loops are divided into outer loop and inner loop. Both loops are with different parameters.

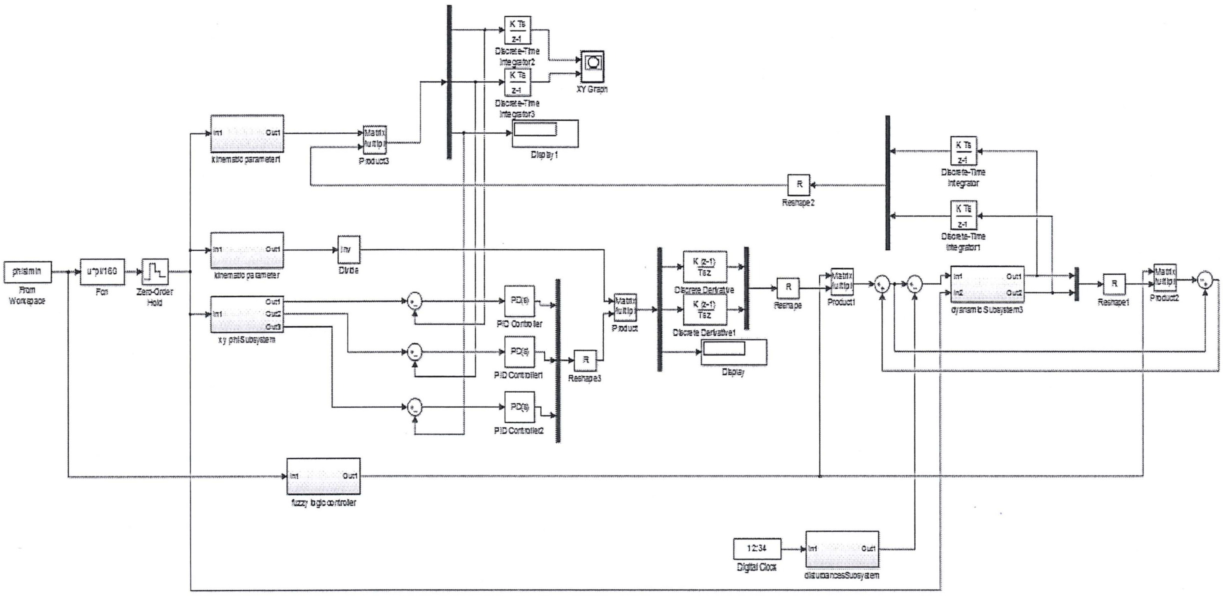


Figure 3.19 Control loop of the system

i. *Outer loop*

The outer loop of the control loop is operated base on kinematic parameter. The angular acceleration, $\ddot{\theta}_R$ and $\ddot{\theta}_L$ are determined from the kinematics equation from the equation (3.7). The SIMULINK block diagram to find the angular acceleration is show in the figure 3.20. PD controller is implemented in the outer loop of the control system to reduce the $\dot{x}_{error}$,$\dot{y}_{error}$ $\dot{\varphi}_{error}$of the path control.

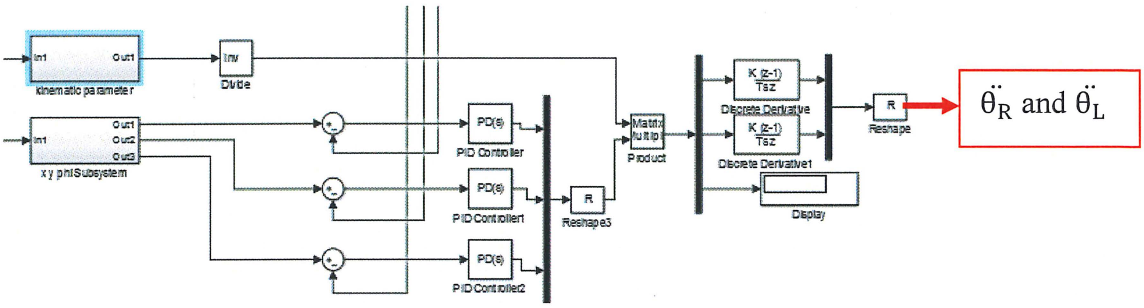


Figure 3.20 The SIMULINK block diagram to find the angular acceleration

ii. *Inner loop*

The inner loop of the control system is operated base on the angular acceleration and Inertia Matrix, IN_R andIN_L. From the equation (3.35), the IN_R and IN_L is multiply with the $\ddot{\theta}_R$ and $\ddot{\theta}_L$ respectively to get the torque. The applied torque is calculated by taking the angular acceleration calculated from the kinematic system multiply with the IN. After that the applied torque becomes the input of the dynamic system to calculate the angular acceleration from the equation (3.21). However, for the actual torque, it is determined by multiply the angular acceleration with the IN. Both applied torque and actual torque are show in the figure 3.21.

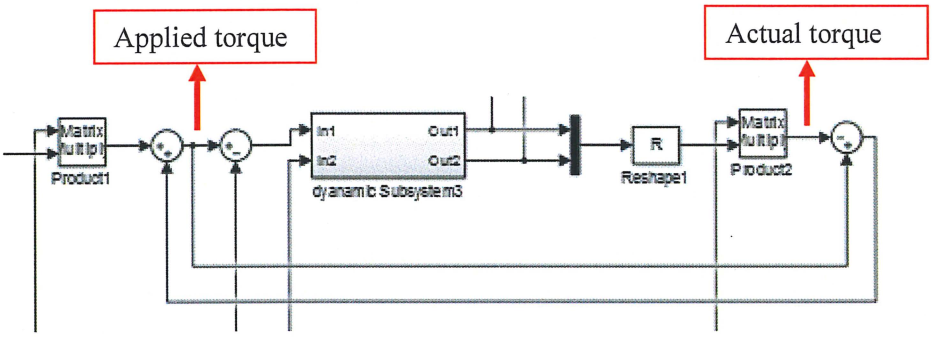
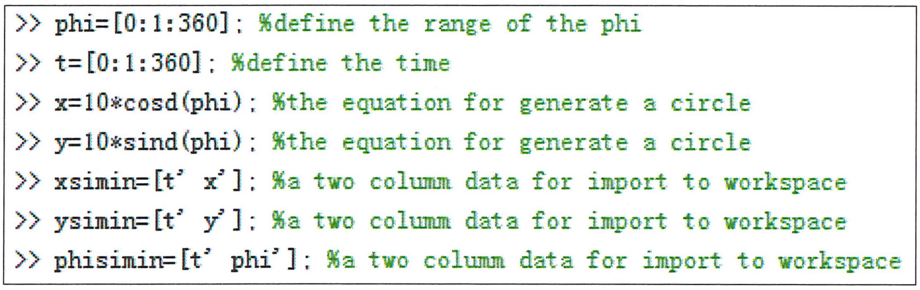


Figure 3.21 Applied torque and actual torque in the inner loop

3.7 Simulation of Control of Wheeled Mobile Robot

The variables x, y and φ are imported from the workspace to SIMULINK. The command in the figure 3.22 to generate the circular path is import from the workspace to SIMULINK.



```
>> phi=[0:1:360]; %define the range of the phi
>> t=[0:1:360]; %define the time
>> x=10*cosd(phi); %the equation for generate a circle
>> y=10*sind(phi); %the equation for generate a circle
>> xsimin=[t' x']; %a two column data for import to workspace
>> ysimin=[t' y']; %a two column data for import to workspace
>> phisimin=[t' phi']; %a two column data for import to workspace
```

Figure 3.22	The command to define the variables for circular path

The range for the x, y and φ value are defined. Moreover, in order to generate a circle, equation (3.36), (3.37) are set in the command.

$$X= 10 \cos \varphi \qquad (3.36)$$

$$Y= 10 \sin \varphi \qquad (3.37)$$

In the SIMULINK, the 'from workspace' bock diagram is use to import the data from the workspace. The figure 3.23 shows the block diagrams that import the data from workspace. The φ is convert into radian and the 'zero order holder' bock diagram is to make sure that the data is imported one by one.

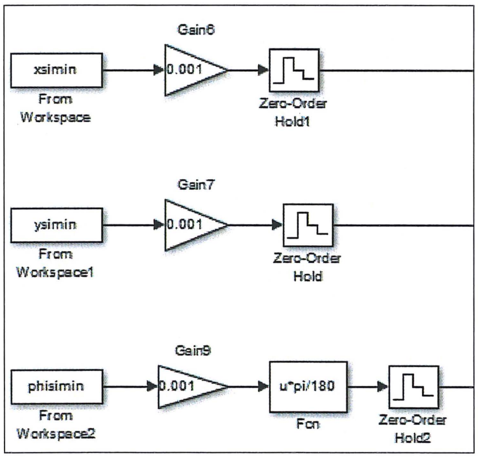


Figure 3.23	The SIMULINK block diagram for import data.

In the simulation, the assumptions of the wheel mobile robot parameters are show in the table 3.3.The parameter of the robot included: mass of the robot, mass of the wheel, movement of inertia of the robot and movement of inertia of the wheel, radius of the wheel, length of the mobile robot and distance between the references point and centre point.

Table 3.3: Parameter of the robot

Mass of the robot, m	36 kg
Mass of the wheel, m_w	0.8 kg
Moment of inertia of the robot, I	18 kgm^2
Moment of inertia of the wheel, I_w	0.00818kgm^2
Radius of the wheel ,r	0.1m
Length of the mobile robot., b	0.02m
Distance between references point and centre point, d	0.5m

3.8 System Block Diagram for Control the Wheeled Mobile Robot Practically

The wheeled mobile robot is controlled practically by interfacing the Arduino and MATLAB SIMULINK as shown in the figure 3.24 below. The encoder attached on the wheel of the mobile robot will determine the pulses per revolution of the wheel in order to determine the rpm of the wheel. The pulses signal of the encoder will send to the SIMULINK from the Arduino. After that from the SIMULINK, the system will send the PWM signal and send back to Arduino to move the robot.

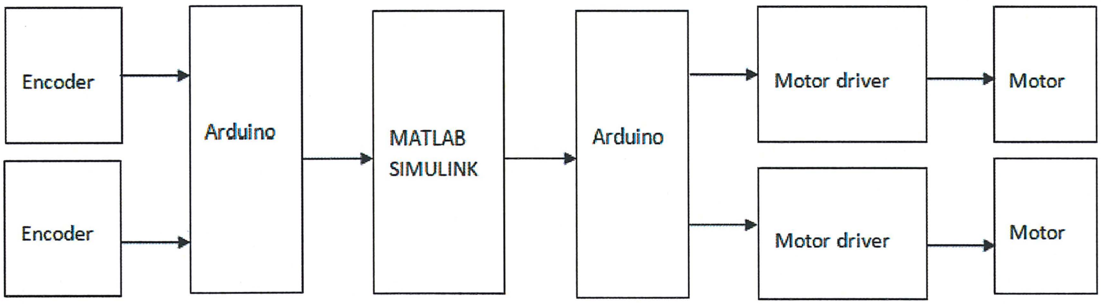
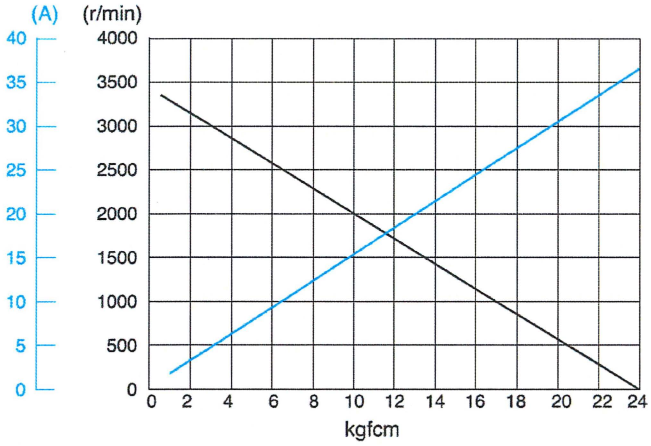


Figure 3.24 System block diagram for control the wheeled mobile robot.

The pulses of the encoder are converted into RPM by using the equation (3.36):

$$\text{RPM} = \frac{(\text{mesured pulses})\times(60 \text{ sec per min})}{\text{numberof pulses in one revolution}} \tag{3.36}$$

The torque can be calculated from the graph 3.1 below by using the equation (3.38):



Graph 3.1 RPM-torque graph
Sources: DC motor datasheet

$$T = (kt \times rpm) + c \tag{3.38}$$

Where; kt = gradient of the graph, c= constant

Gradient of the graph:

$$kt = \frac{0 - 2000}{24 - 10}$$

$$= -142.87$$

When rpm=2000 r/min, T=10 kgfcm,

$$10 = (-142.87 \times 2000) + c$$

$$c = 3248.57$$

Thus, the torque can be calculated by using the equation (3.39):

$$T = (-142.87 \times rpm) + 3248.57 \tag{3.39}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides the performance analysis results of the control of wheeled mobile robot. The result of fabrication of robot and both simulation and actual control of the wheeled mobile robot are shown in this section. The data and results are discussed in details.

4.2 Control of Wheeled Mobile Robot

The simulation of the control of the wheeled mobile robot is simulated in MATLAB SIMULINK. To control the wheeled mobile robot in restricted environment, the mobile robot is simulated to move in circular path. The references path and the actual path are compared in the section below.

The simulation of the control of wheeled mobile robot move in circular path is shows in the figure 4.1 and 4.2. The reference path and actual path of the wheeled mobile robot are compared.

For the simulated path, the starting point of the wheeled mobile robot is at origin point so the mobile robot will move from the origin to the circle path. By comparing both references and actual path, the movement of the mobile robot are similar, it can be said that the mobile robot is move in its actual path with zero track error.

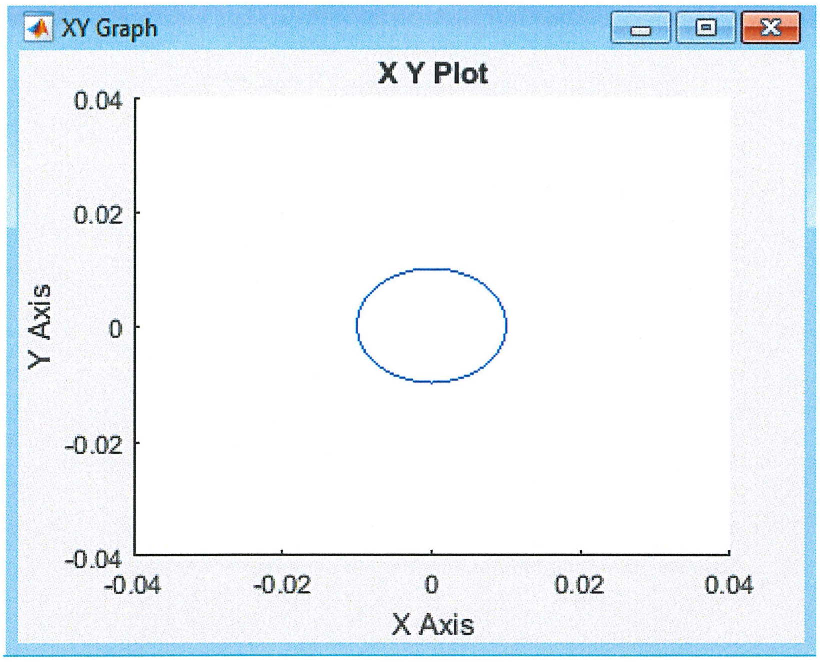


Figure 4.1 Reference path for circular path

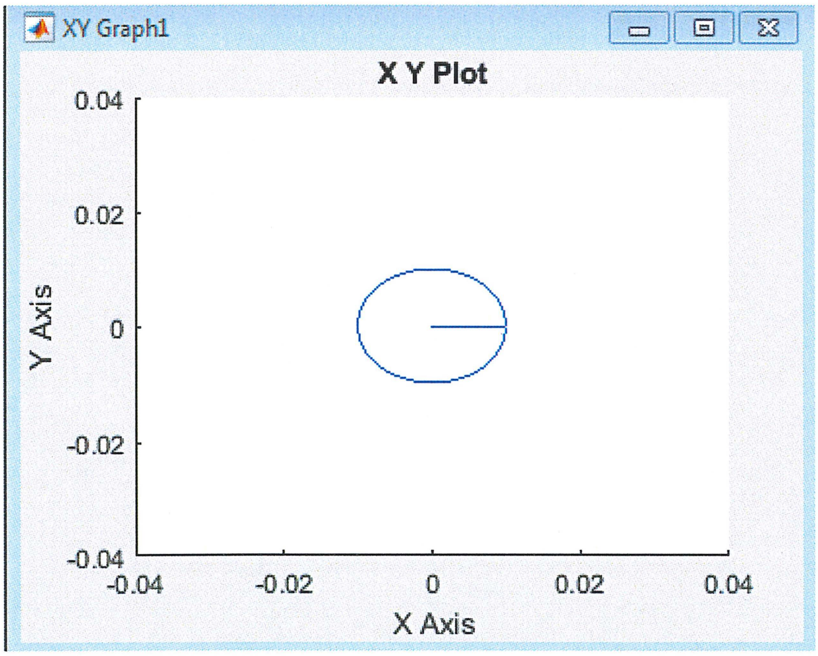
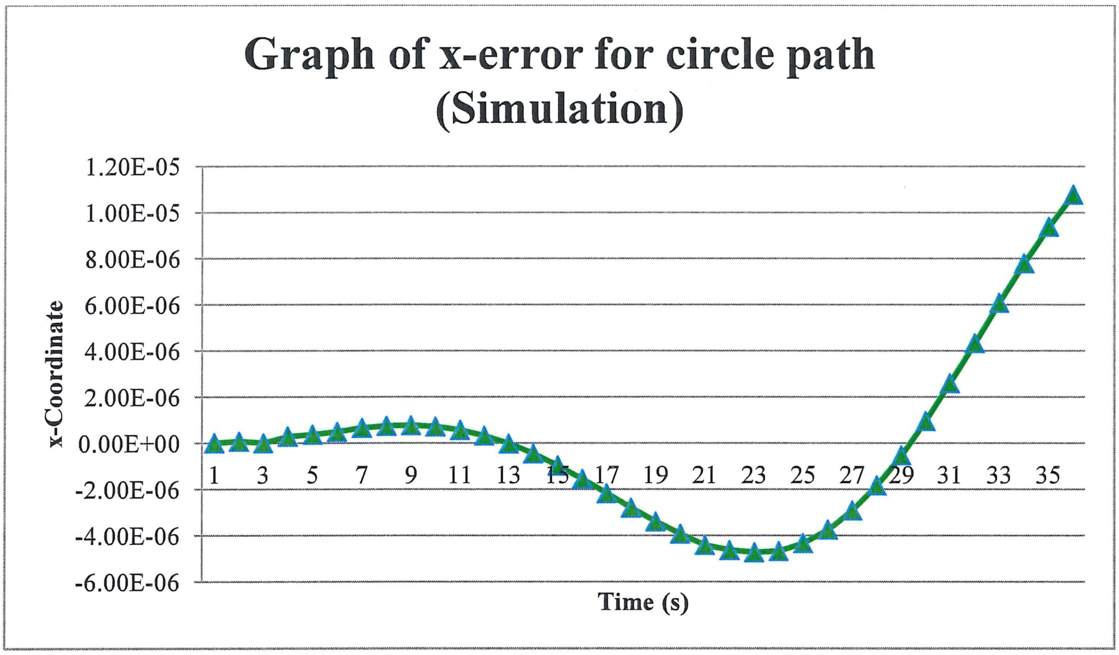
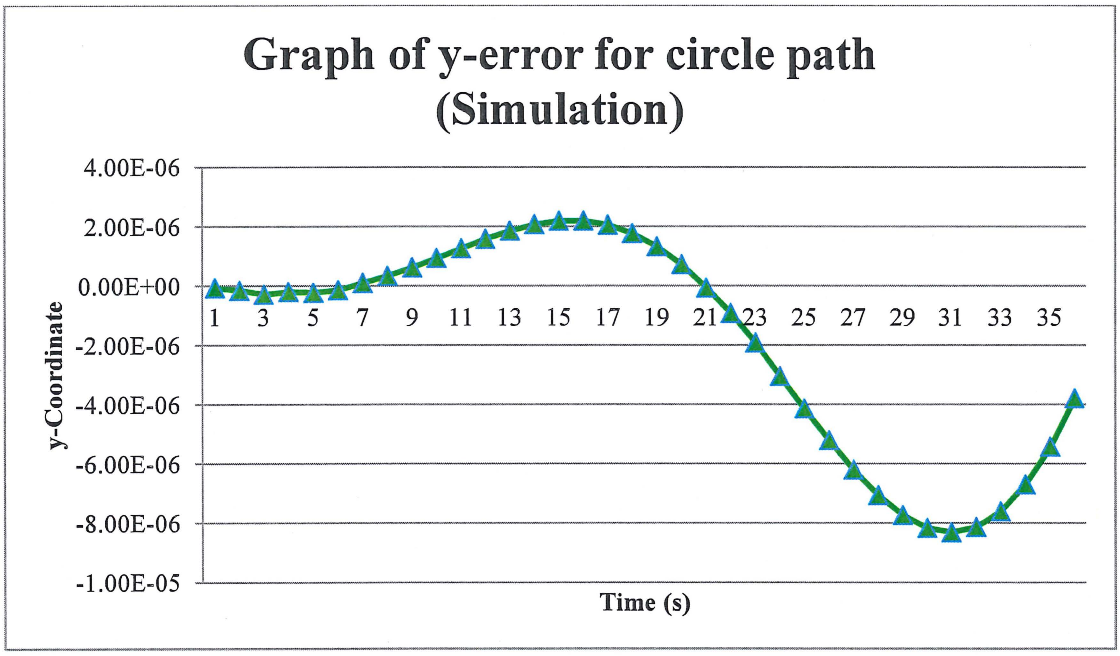


Figure 4.2 Actual path for circular path



Graph 4.1 Graph of x-error for circular path in simulation



Graph 4.2 Graph of y-error for circular path in simulation

The graph 4.1 and 4.2 shows the graph of x-error for circular path and y-error for circular path. The x and y references path is compared with the x and y actual value from the simulation for every 10 s.From the graph, the maximum error of the x-coordinate is 1×10^{-5} while the maximum error of the y-coordinate is 8×10^{-6}. Both errors are very small, so the mobile robot is move in the actual path with minimum track error. As from the graph, there is only slightly error between the xy-references values and xy-actual values, which mean that the errors are small, so it can be said that the system is robust.

Besides that, the wheeled mobile robot also control practically in straight line as show in the figure 4.3. The mobile robot is set to move in straight line for 20s after that the mobile robot will stop.

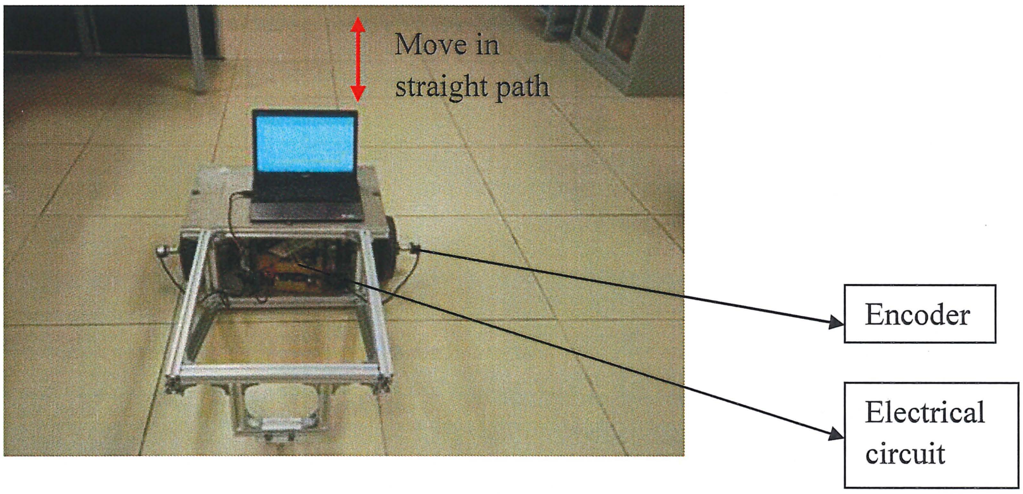


Figure 4.3 Control the wheel mobile robot in straight line practically

However, the mobile robot is not able to move in straight line. The bad performance in the practical part may due to many reasons. In the practical part, in order to make the wheeled mobile robot to move in its reference path, there are many factors need to be considered, such as the weight of the mobile robot, friction of the wheel of the mobile robot with the road, and the friction of the motor shaft with the bearing.

From the design, the mobile robot is supported by the bearing and the wheel, in addition, the mobile robot is made by aluminum plate and aluminum profile, so the weight of the mobile robot is around 35kg to 40kg which will cause the friction between the shaft and bearing become high. Moreover, due to the parallax error during assemble the bearing and motor shaft on the body of the mobile robot, it may cause the wheel not align and unbalance friction act on the wheel. This factor may affect the mobile robot unable move in straight line.

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter will describe the conclusion for this project and some recommendation of the project in the future.

5.2 Conclusion

In a nutshell, the objective of the project is fully achieved, which is fabricated the wheeled mobile robot, apply the Proportional Derivative-Active force control (PD-AFC) algorithm with different types of restricted environments, and control the wheeled mobile robot in restricted environment with zero track error. However, in both straight and circular path, the errors between the references value and actual values are approximately zero. So it is conclude that the PD-AFC algorithm is able to control the wheeled mobile robot in simulation part with minimum track error. For the practical part, due to many factors, the mobile robot is not follow exactly the reference path, so it should be solved for future improvement.

5.3 Recommendation

However, for this project, there is still has some recommendation for the further improvement:

1. Improve the mechanical fabrication part, so that the wheels of the mobile robot are aligned.

2. Improve the controller, so the mobile robot will able to move with zero track error.
3. Improve the function of the mobile robot, such as add on some sensor for avoid the obstacle.

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APPENDIX

CONTROL OF WHEELED MOBILE ROBOT IN RESTRICTED ENVIRONMENT

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Abstract — **This paper is a study of control of wheeled mobile robot in restricted environment. A wheeled mobile robot with 3 wheels is fabricated control by proportional derivative active force control (PD-AFC) to move in a pre-planned restricted environment to perform minimum track error. A control system with two loops, outer and inner loop is designed to control the wheeled mobile robot. Fuzzy logic controller is implemented in the SIMULINK to estimate Inertia Matrix that will be used to calculate the actual torque applied on the wheeled mobile robot. The mobile robot is tested in circular path. The actual path and desired path are compared.**

I. INTRODUCTION

Mobile robot plays an important role in society today. There are several types of mobile robot, such as legged, wheeled and tracked mobile robot (Elyoussef, De Pieri, Moreno, & Jungers, 2012).. Wheeled mobile robots are used in many applications especially in factory and some restricted environments that human cannot perform (Abdalla, 2013).

The motion of the wheeled mobile robot is controlled by controller such as Proportional-Integral-Derivative (PID), Fuzzy logic control (FLC), Active force control (AFC). (Deng et al., 2014) By implementing a useful controller, the motion of the wheeled mobile robot will become stable and able to move in different types of trajectories with zero track error (Ali, Yusoff, Hamedon, & Yusssof, 2015).

Moreover, Tele-operated system which controls the robot remotely by human will cause inaccurate control operation of mobile robot. Tele-operated mobile robot control system may need the manpower and some error un-estimated disturbances may occur during the control operation. Therefore, an appropriate controller should be use to increase the predictability of the mobile robot's behaviour, decrease tracking errors and can make sure that the control of mobile robot is in robust enough.

In this research, the Active force control (AFC) algorithm will be implemented to a three wheeled mobile robot. The motion of the mobile robot is planned and the actual with desired paths of the wheeled mobile robot are compared. Moreover, both kinematic and dynamic modelling of the mobile robot is considered. In this project, it is only focus on the three wheels differential drive mobile robot which will be tested in circular path.

II. METHODOLOGY

a. *Modelling of robot*

The mobile robot comprises of three wheels driving system, as show in figure 1. r is the radius of the wheel and L is the distance between the wheels of mobile robot. The motion of the mobile robot can be described in global and local coordinate system.

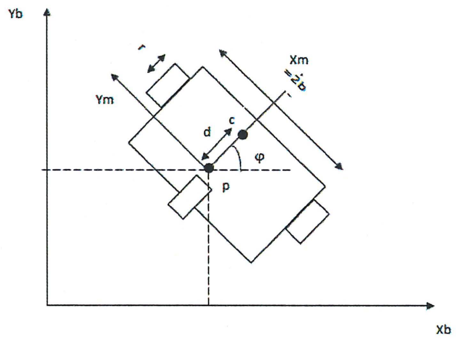


Figure 1: Motion of wheeled mobile robot in local and global coordinate system

Kinematic modelling

The mobile robot is moved with two differential drive wheels and a castor wheel, so the velocity is:

$$v = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \quad (1)$$

The difference between angular velocity of right and left wheels can be illustrated as in Equation (2).

$$\dot{\varphi} = \begin{bmatrix} \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \quad (2)$$

The local coordinate system is show in Equation (3).

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos\varphi & -d\sin\varphi \\ \sin\varphi & d\cos\varphi \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \dot{\varphi} \end{bmatrix} \quad (3)$$

The Equation (3) thus can be written in the term of angular velocity $\dot{\theta}_R$ and $\dot{\theta}_L$ as show in equation (4)

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\varphi - \frac{dr}{2b}\sin\varphi & \frac{r}{2}\cos\varphi + \frac{dr}{2b}\sin\varphi \\ \frac{r}{2}\sin\varphi - \frac{dr}{2b}\cos\varphi & \frac{r}{2}\sin\varphi - \frac{dr}{2b}\cos\varphi \\ \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \quad (4)$$

Dynamic modelling

The dynamic of the mobile robot can be derived using Lagrange equation as show in Equation (5).

$$\frac{d}{dt}\left(\frac{\delta k}{\delta \dot{q}}\right) - \frac{\delta k}{\delta q} = \tau_i - A^T(q)\lambda \quad (5)$$

Where; k = kinetic energy, q = coordinate system, τ_i = exerted torque on the robot, $A^T(q)$ = constraints of robot

The total kinetic energy can be written as in Equation (6):

$$KE_{total} = KE_{body} + KE_{RW} + KE_{LW} \quad (6)$$

The Equation (7) can represent in general form of Lagrange Equation:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} = B(q)r - A^T(q)^{\lambda} \quad (7)$$

Where:

$$M(q) = \begin{bmatrix} m & 0 & 2m_w d\sin\varphi & 0 & 0 \\ 0 & m & -2m_w d\cos\varphi & 0 & 0 \\ 2m_w d\sin\varphi & -2m_w d\cos\varphi & I & 0 & 0 \\ 0 & 0 & 0 & I_w & 0 \\ 0 & 0 & 0 & 0 & I_w \end{bmatrix}$$

$$V(q,\dot{q}) \begin{bmatrix} 2m_w d\dot{\varphi}^2\cos\varphi \\ 2m_w d\dot{\varphi}^2\sin\varphi \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \quad B(q)r = \begin{bmatrix} \tau_R & 0 \\ 0 & \tau_L \end{bmatrix}$$

b. Robot design

Figure 2 shows the 3D view of wheeled mobile robot. The wheeled mobile robot is non-holonomic mobile robot, which consists of two differential wheels and one castor wheel.

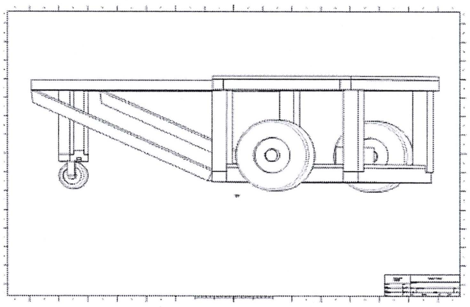


Figure 2: Design of wheeled mobile robot

c. Controller design

Figure 3 shows the design of PD-AFC implemented in the control of wheeled mobile robot. The control loop consists of two loops, outer loop and inner loop. PD controller is in the outer loop of the control loop. The inner loop of the control loop is AFC control strategy, which is able to make the dynamic system stable and robust.

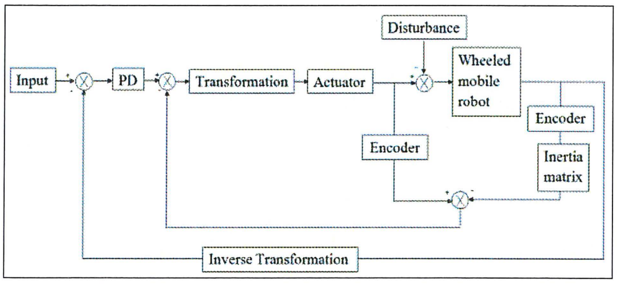


Figure 3: PD-AFC scheme

d. Fabrication of robot

Figure 3 shows the wheeled mobile robot. The body structure of the mobile robot is made of 30x30mm and 40x40 aluminium profile. 10mm thick aluminium plate is use as the cases of the mobile robot.

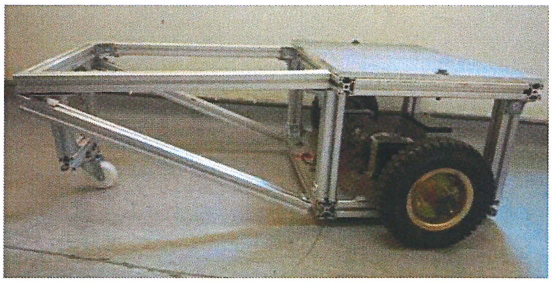


Figure 4: Wheeled mobile robot

Table 1: Mechanical part fabrication

No.	Parts	Material	Process
1	Body support	Aluminium	Sawing & Drilling
2	Body casing	Aluminium	Sawing & Drilling
3	Motor shaft	Mild steel	Turning, Drilling, Electric Discharges & Welding

III. RESULT & DISCUSSION

a. MATLAB simulation

The simulation of the control of the wheeled mobile robot is simulated in MATLAB SIMULINK. To control the wheeled mobile robot in restricted environment, the mobile robot is simulated to move in circular path. The references path and the actual path are compared in the section below.

In the simulation, the assumptions of the wheel mobile robot parameters are show in the table below. The parameter of the robot included: mass of the robot, mass of the wheel, movement of inertia of the robot and movement of inertia of the wheel, radius of the wheel, length of the mobile robot and distance between the references point and centre point.

Table 2: Parameter of the robot

Mass of the robot, m	36 kg
Mass of the wheel, m_w	0.8 kg
Moment of inertia of the robot, I	18 kgm^2
Moment of inertia of the wheel, I_w	0.00818kgm^2
Radius of the wheel ,r	0.1m
Length of the mobile robot., b	0.02m
Distance between references point and centre point, d	0.5m

i. Circular path

The simulation of the control of wheeled mobile robot move in circular path is shows in the figure 5 and 6. The reference path and actual path of the wheeled mobile robot are compared.

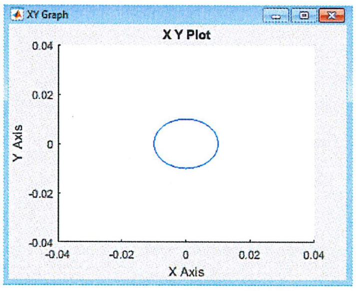


Figure 5: Reference path for circular path

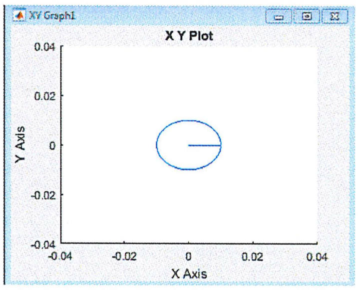
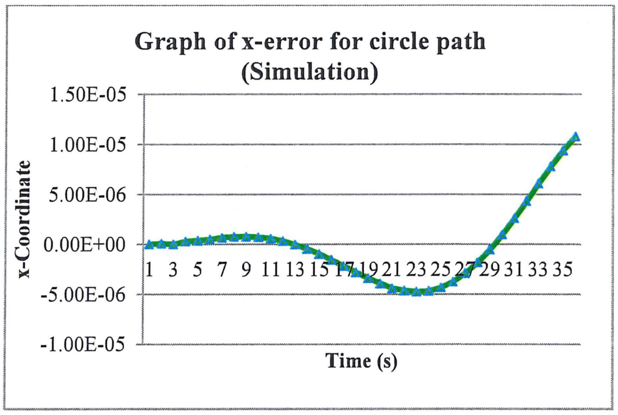
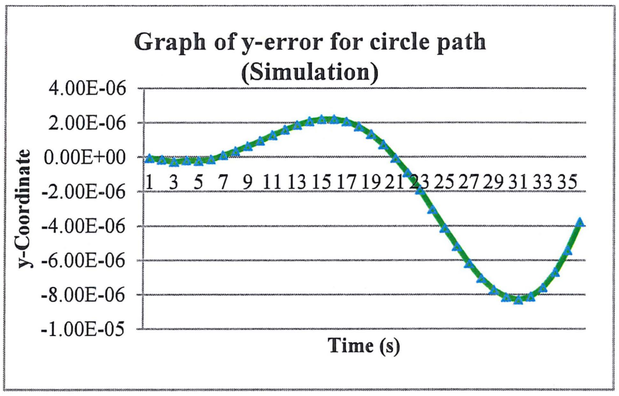


Figure 6: Actual path for circular path



Graph 4.1: Graph of x-error for circular path in simulation



Graph 4.2: Graph of y-error for circular path in simulation

The graph 4.1 and 4.2 shows the graph of x-error for circular path and y-error for circular path. The x and y references path is compared with the x and y actual value from the simulation for every 10 s.From the graph, the maximum error of the x- coordinate is 1×10^{-5} while the maximum error of the y-coordinate is 8×10^{-6}. Both errors are very small, so the mobile robot is move in the actual path with minimum track error. As from the graph, there is only slightly error between the xy-references values and xy-actual values, which mean that the errors are small, so it can be said that the system is robust.

Besides that, the wheeled mobile robot also control practically in straight line as show in the figure 7. The mobile robot is set to move in straight line for 20s after that the mobile robot will stop.

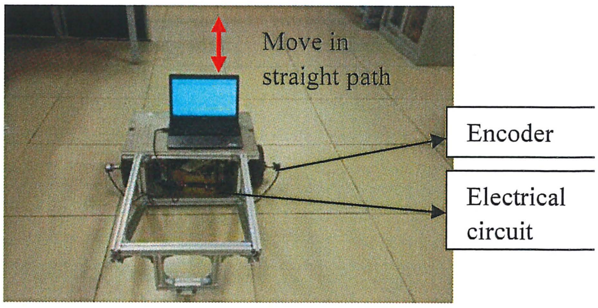


Figure 7: Control the wheel mobile robot in straight line practically

However, the mobile robot is not able to move in straight line. The bad performance in the practical part may due to many reasons. In the practical part, in order to make the wheeled mobile robot to move in its reference path, there are many factors need to be considered, such as the weight of the mobile robot, friction of the wheel of the mobile robot with the road, and the friction of the motor shaft with the bearing.

From the design, the mobile robot is supported by the bearing and the wheel, in addition, the mobile robot is made by aluminum plate and aluminum profile, so the weight of the mobile robot is around 35kg to 40kg which will cause the friction between the shaft and bearing become high. Moreover, due to the parallax error during assemble the bearing and motor shaft on the body of the mobile robot, it may cause the wheel not align and unbalance friction act on the wheel. This factor may affect the mobile robot unable move in straight line.

IV. CONCLUSION

In a nutshell, the objective of the project is fully achieved, which is fabricated the wheeled mobile robot, apply the Proportional Derivative-Active force control (PD-AFC) algorithm with different types of restricted environments, and control the wheeled mobile robot in restricted environment with minimum track error. However, in circular path, the errors between the references value and actual values are approximately zero. So it is conclude that the PD-AFC algorithm is able to control the wheeled mobile robot in simulation part with minimum track error.

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