A STUDY OF MOBILE ROBOT MOTION CONTROL USING ACTIVE FORCE CONTROL

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ABSTRACT

The project describes a new strategy to control the motion of wheeled mobile robot (WMR) using active force control (AFC) based on its capability to eliminate the presence of disturbances. A proportional derivative active force control (PDAFC) scheme is incorporating with artificial intelligent techniques, namely, fuzzy logic (FL) to effectively calculate the inertia matrix which is multiplied by acceleration to give the actual torque. The heading rotation of a wheeled mobile robot is not always perfect because the workspace of an object is normally filled with known or unknown disturbances. The robustness and effectiveness of the proposed control scheme are investigated and compared with traditional controller like PD controller. The simulation study verify that the proposed system is performing excellently even in the presence of uncertainties. The simulated system was validated through simulation study carried out on circle and leaf trajectory by using software interface (MATLAB / SIMULINK). The obtained results of AFC and PDAFC controller demonstrate better performance in comparison with PD controller.

ABSTRAK

Projek ini menerangkan strategi baru iaitu mengawal pergerakan robot mudah alih beroda (WMR) dengan menggunakan kawalan daya aktif (AFC) berdasarkan keupayaannya untuk menghapuskan kehadiran gangguan. Skim berkadar terbitan kawalan daya aktif (PDAFC) dilaksanakan secara khas untuk projek ini dengan menggabungkan satu jenis teknik pintar, iaitu logik kabur (FL) untuk mengawal putaran tajuk robot mudah alih beroda (WMR) secara berkesan atau teguh dan digunakan untuk mengira matriks inersia yang didarab dengan pecutan untuk memberikan tork yang sebenar. Putaran menunjukkan robot mudah alih beroda tidak selalunya sempurna kerana ruang kerja objek biasanya dipenuhi dengan gangguan yang diketahui atau tidak diketahui. Kemantapan dan keberkesanan skim kawalan yang dicadangkan telah disiasat dan terbukti bahawa ia lebih berkesan berbanding dengan pengawal tradisional seperti pengawal PD. Simulasi dan kajian eksperimen mengesahkan bahawa sistem boleh melakukan penghapusan gangguan dengan cemerlang walaupun dihadiri gangguan yang tidak tentu. Sistem simulasi telah dilengkapkan dan disahkan melalui kajian eksperimen yang dijalankan pada trajektori bulatan atau daun dengan menggunakan antara muka perisian (MATLAB / SIMULINK). Keputusan yang diperolehi telah menunjukkan AFC dan PDAFC adalah pengawal yang lebih baik berbanding dengan pengawal PD.

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LIST OF SYMBOLS

+	Addition
( )	Calculate expression inside first
[ ]	Calculate expression inside first
/	Division
÷	Division
=	Equality
*	Multiplication
×	Multiplication
%	Percentage
Σ	Total sum
-	Subtraction
m	Meter

LIST OF ABBREVIATIONS

AFC	Active Force Control
AFCCA	Active Force Conventional Crude Approximation
AFCAIL	Active Force Control and Iterative Learning
ATE	Average Tracking Error
DOF	Degree of Freedom
EAFC	Evolution Active force Control
FIV	Friction Induced Vibration
FL	Fuzzy Logic
IAFC	Intelligent Active Force Control
RAC	Resolved Acceleration Control
PD	Proportional Derivative
PDAFC	Proportional Derivative Active Force Control
PIAFC	Proportional-Integral Active Force Control
PID	Proportional Integral Derivative
MM	Mobile manipulator
MTE	Mean Tracking Error
WMR	Wheel Mobile Robot

CHAPTER 1

INTRODUCTION

1.1 Introduction

Mobile robot with wheels being considered as one of the major concerns in this world of advanced technology. Therefore, people always seek to use mobile robot throughout the manufacturing plant that a good mobile robot should have a superior locomotion mechanism. In some cases like dangerous and hospitable environments, it is impossible for a human operator to control a mobile robot motions. Sometimes, mobile robot is capable to do automatic locomotion and environment observation under condition absence of oxygen that human cannot do at hostile environment such as Mars. Moreover, commercially viable mobile robot can polishes the factory floor, keeps guard in a house, provides tours in a museum, or offer some guidance in a supermarket.

Basic motion problem of wheeled mobile robot includes high computational complexity of the planning problem, dynamic environment with including multiple robots and restricted mobility of robotic vehicle with analysis of elementary tasks. Examples of reactive motion involve avoid obstacles and tracking a target. To solve the locomotion problems or fabricate a successful mobile robot, the mobile robotics must be trained by dynamic and control theory; mechanism and kinematics so that mobile robots can allocate them self with motion controller using robust controller such Active Force Controller.

1.2 Project Background

For many years, wheeled mobile robot has been considered as a good human helper in daily life. Nowadays, the using of controller for mobile robot is followed closely by many countries or area either in academic or industrial an aspect which contributes indelibility in such way to the country economics. A good wheeled mobile robot should be able to provide all feasible directions of instantaneous motion. Most of mobile robot uses wheel as their locomotion and the three wheels system seems to be the most practical in stability. In mobile robot motion, we care don’t only about stability of a mobile robot but also on how it is moving straight path or circle path.

In addition, a good wheeled mobile robot should be expert at stability, good contact characteristics and able moving in a variety of environments. For example, a wheeled mobile robot is able to perform well if there is stable center of gravity, precise angle of contact and good structure.

On the other hand, a very good wheeled mobile robot should be perfect to avoid all obstacles during any task. Therefore, the study of motion model of Wheeled Mobile Robot is very important. It provides all feasible directions of instantaneous motion.

Furthermore, Active Force Control scheme is one of the most useful controller that can observe the tracking error very well. A well-functioning Active Force Controller can compare the actual value with ideal value that coming from applied torque and acceleration sensor parameter. There are always an external and inner loops in Active Force Controller. External loop usually functions as kinematic system and contain traditional controller like PD controller. The inner loop always functions as dynamic system and contains the Active Force Controller strategy.

Active Force Controller actually involves the use of actuators that are used to apply torque to the driving wheels and also include sensors that are used to measure the angular acceleration of driving wheels in real-world environment. Besides that, Active Force Controller is very effectively to recompense the disturbances. The actual torque of the AFC controller is calculated using inertia matrix which is using Artificial Intelligence methods like Fuzzy Logic. Transformation matrix is used to convert from local to global coordinate system and vice versa. Figure 1.1 below shows a common way for operating Active Force Control Scheme.

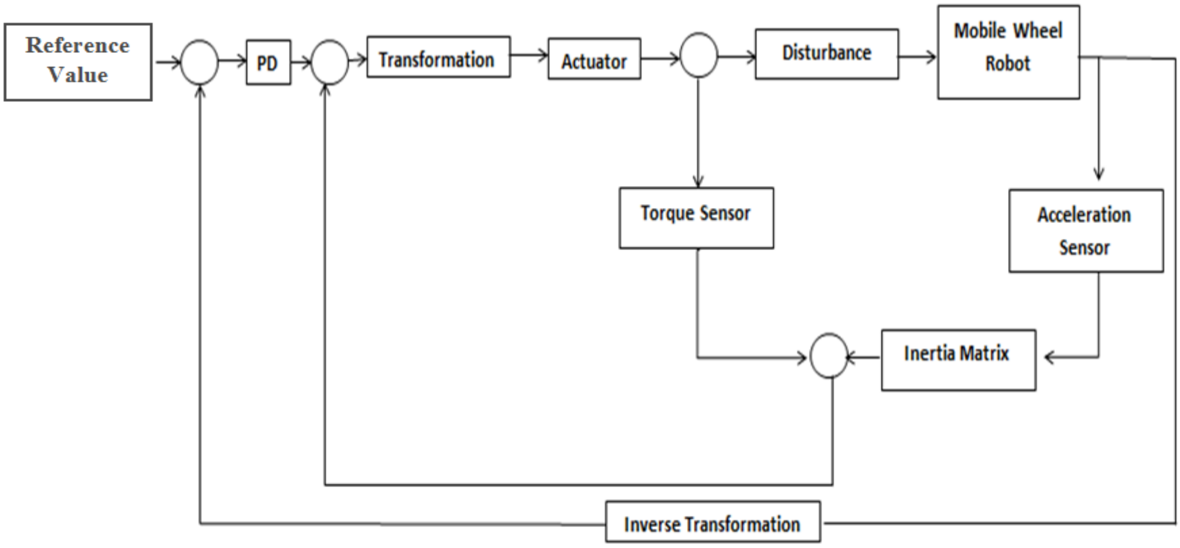


Figure 1.1: Active Force Control Scheme

1.3 Problem Statement

Mobile robot motion control using Active Force Control can make the wheeled mobile robot more stable which resulted by less value of tracking errors. The mobile robot can also be very robust even though in presence of obstacle and disturbances. The active force controller has been proven by many journals that it led to more robust and effective in comparison to the traditional control methods like PID, PD, and PI controller.

The mobile robot that controled using active force control is assumed to be moved in x and y direction on a flat plane as described in Figure 1.2. The wheels of mobile robot are three wheels, two differential and Castor wheels. In addition, the wheels of the Non-holonomic mobile robot are assumed to move in pure rolling and no slipping on the ground. On the other hand, the Non-holonomic mobile robot can only move in the Feedward/backward axis of driving wheels and it cannot do any movement in sidewise.

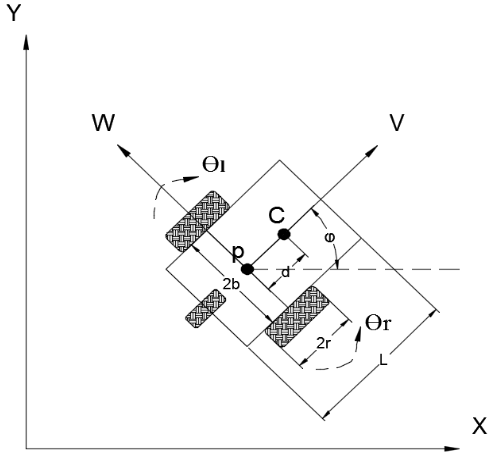


Figure 1.2: Local /global coordinate system with mobile robot dimension

L: Length of the mobile robot
r : Mobile robot wheels radius
d : Center of mobile robot, c and the driving wheel shaft, p displacement
2b : Distance between two wheels
θ : Angular velocity (movement generated by motor when switch wheel)
φ : Heading rotation (rotation of mobile robot in counter clockwise)
X and Y axis : Global coordinate system
W and V axis : Local coordiante system

1.4 Objectives

This study is concerned on wheeled mobile robot motion control. The objectives of this study are:

i. To model wheeled mobile robot with three wheels using active force control.
ii. To implement active force control in simulation study.
iii. To compare the AFC scheme with other controllers like PD in circle and leaf trajectory.

1.5 Project Scopes

The scope states some kind of limitation that should be followed. Beside that, the scope also is intended to identify the area of focus and boundaries of the study. The limitation of wheeled mobile robot are as following:-

i. Three wheels
ii. Two wheel differential Drive
iii. Castor (3 DOF)
iv. Each wheel rolls on the ground without slipping (longitudinally) nor skidding (sideways)
v. To perform active force control with symbol path like circle or straight path.

1.3 Structure of Report

This report has only four chapters. The first chapter is introducing the mobile robot motion using active force control. Besides that, first chapter also describes the background of study, problem statement, objectives, scopes of the study and the structure of report.

Next chapter focuses on the literature review based on the previous studies of wheeled mobile robot. It includes the fundamental of wheeled mobile robot, the factors that influence wheeled mobile robot movement and parameters of active force control. So, this chapter has major influences to increase better understanding on mobile robot and is very helpful to design the methodology of study.

Chapter 3 describes the methodology to solve the problem. The methods and procedures that have been use to reach the objectives of this study.

Chapter 4 describes the modeling of wheeled mobile robot. Besides that, chapter 4 also explained the equation of kinematic and dynamic model. This chapter also has presented the project details and method of simulation used.

The results and discussions are presented in chapter 5. The comparison between AFC controller and PD controller are discussed in this chapter. Besides that, average percentage of tracking error was compared among three controller which are PD, AFC and PDAFC controller. Finally, the outcome of this study was discussed.

The final chapter of this thesis consists of conclusion and recommendation for future improvement work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review is very important to show the ongoing researches that are related with this topic. Therefore, this chapter is focusing on the review of the previous studies in wheel mobile robot motion control using active force control. This review is helpful for the further development of this research.

2.2 Active Force Control

The study by (HEWIT, 1981) first applied the technique known as active force control (AFC) successfully to a robotic arm. They proposed a practical and robust technique to compensate for internal and external disturbances of a mechatronics/machinery system by employing an internal force error feedback control based on real-time acceleration and force measurements. The general form of the AFC scheme is depicted in Figure 1.1.

The measurement of acceleration with estimated Inertia Matrix will be compare with applied torque to estimate torque disturbance can be written as in Equation (2.1):

$$\tau_d^* = \tau - \mathrm{IN}\ddot{\theta} \qquad (2.1)$$

where,

τ_d^* : Estimated torque disturbance effect on the motor wheels
τ : Torque of actuator
IN: Estimated Inertia Matrix
$\ddot{\theta}$: Actual acceleration

The AFC method is concerned on the way to ensure that the system is stable and robust even in the presence of known or unknown disturbances. The main advantage of the method is that it can give a compensating action using mainly the estimated or measured values of certain parameters. This method has the benefits of reducing the mathematical complexity of the robot system that is known to be highly coupled and non-linear. One of the alternatives is by implementing the PD scheme to the AFC. The Figure 2.1 shows the combination of inner and external loop in order to achieve a complete motion control of wheeled mobile robot.

2.3 Fuzzy Logic

Fuzzy set theory was first introduced by (ZADEH, 1965), and handles the concept of partial truth. It deals with fuzziness in the real world and simulates a human’ s subjective thinking by incorporating the inherent imprecision of human thought processes. Based on linguistic variables and if-then rules, fuzzy systems are suitable for systems that are based on mathematical model that is difficult to derive, or systems dealing with nonlinear or incomplete information

2.3.1 Fuzzy Sets and Membership Functions

(JAHANABADI 2010) is state that a classical set or crisp set is a set with a boundary which defines values of a given set as either true or false, but not both. According to classical and conventional logic, an element determinately is or is not a member of a particular set: there is no middle area. Classical logic is an important tool in mathematics, science, and other varying applications. However, it does correspond to human nature and human thoughts, which are always abstract and imprecise.

In contrast to a crisp set, a fuzzy set is “a class of objects with a continuum of grades of membership”. In the fuzzy sets, Zadeh also introduces the notion that “such a set is characterized by a membership function which assigns to each object a grade of membership ranging between zero and one” first proposed in 1965, fuzzy sets are extended forms of classical sets that can deal with values between “completely true” and “completely false”. Instead of two-valued (crisp) set in which the boundary of each class is clearly defined, a fuzzy set is multi-valued; that is, matters are expressed by degree of truth.

For a fuzzy set, a membership function (MF) is a mathematical function that gives numerical meaning to a fuzzy set. It describes how each point in the input area is mapped to a membership value (or a degree of membership) between 0 and 1. The membership function is represented by a graphical curve of the magnitude of participation for each input. The MF expresses the degree to which an object belongs to a fuzzy set, and the only condition it must satisfy is that it must vary between 0 and 1. This condition identifies one of the biggest differences between crisp and fuzzy sets: crisp sets always have a single MF (either zero or one), but each fuzzy set has an infinite number of MFs which could describe it. Furthermore, there is no unique MF for each fuzzy set, because it depends on the characters and applications desired for that set.

2.3.2 Linguistic Variables

(JAHANABADI 2010) is state that in our daily lives, our decision making is mainly based on linguistic rather than numerical information. The conventional approach is convenient for dealing with scientific or engineering issues precise mathematical models. However, real situations are often uncertain or vague in some way. Most of our traditional analytical and applied tools are comparatively crisp, precise, and definite. However, human beings are accustomed to thinking and communicating spontaneously using nature language, which has been shaped over thousands of years to become convenient and efficient. These natural languages may not exist without vague and imprecise concepts, such as “he is tall,” or “today is very cold”, and these statements take no numerical values and difficult to translate into more precise representations.

2.3.3 If-Then Rules

As mentioned before, fuzzy logic reflects the way human brain works, and makes use of human common sense to perform functions. This characteristic is actualized using a set of rules that replace mathematical formulas in order to define a system’s behavior. These rules are models made by humans, and can be easily generated by imitating a human operator’s behavior without having a deep understanding of system’s mathematical model. Fuzzy rules use linguistic information, which is represented as if-then statements. A fuzzy if-then rule is a conditional statement expressed as:

If x is A then y is B

2.4 Literature review

The study by (HEWIT, 1981) emphasizes Active Force Controller that control the dynamic of a robotics. The problem in this research is about dynamic of a robotic arm and has been solved by applying active force control method which shows better result. There are two main components that AFC is normally used which are accelerometer and torque sensors as a torque sensors have been designed into the robot structure which can cancel out all unknown disturbances. Figure 2.1 shows Active Force Control effective in overcoming steady state errors at T_3.

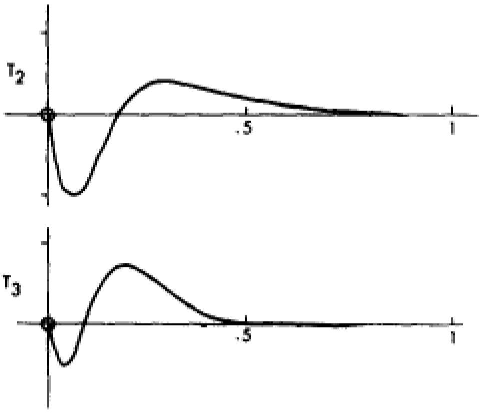


Figure 2.1: Active Force Control effective in overcoming steady state errors

The study by (MAILAH, 2006) emphasizes on Proportional-Integral combined with Active Force Control (PIAFC) which is more robust in comparison to Resolved Acceleration (RAC) for mobile manipulator motion control. Controller of RAC can only manipulate the kinematic strategy while the Proportional-Integral combined with Active Force Control (PIAFC) can recompense the dynamic behaviour that cant only known disturbances but also unknown disturbances. The effectiveness as well as robustness of the control scheme can be seen only if the control schemes use active force control. The result shows that the tracking errors will become less if RAC method is combined with AFC control scheme. Figure 2.2 below shows the different between RAC-AFC and RAC methods. It also shows that the RAC-AFC average track errors are successfully decreased.

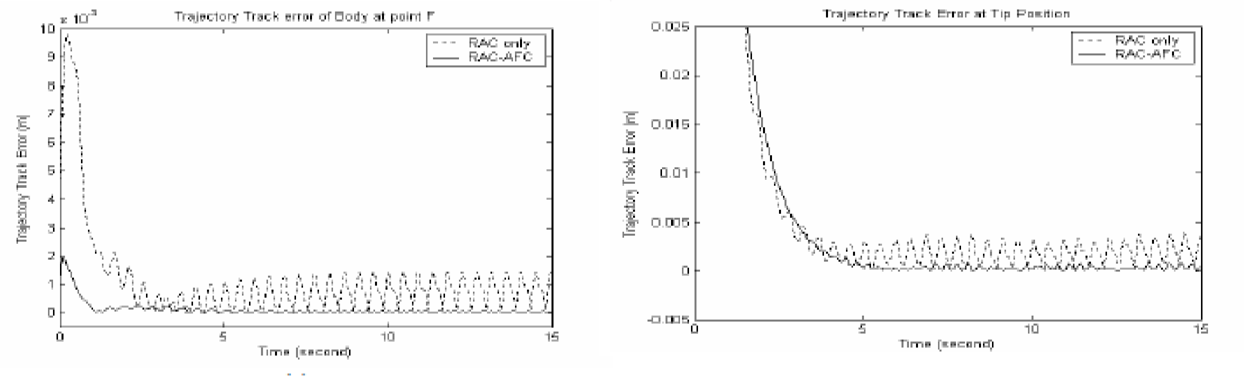


Figure 2.2: Track error with disturbances

The study by (KWEK, 2003) emphasizes an active force control schemes that has been applied on a series of simulation studies on the 5-link biped robot. Then, the control system represent robust and stable behaviour in presence of the influence of disturbances using AFC control scheme. AFC scheme is succeeded to compensate external disturbances acting on the biped system. The quadratic cost function of tracking errors are also minimized by predictive controller based AFC. Figure 2.3 shows the mean tracking error generated by PD, AFCCA and AFCAIL control schemes with disturbances.

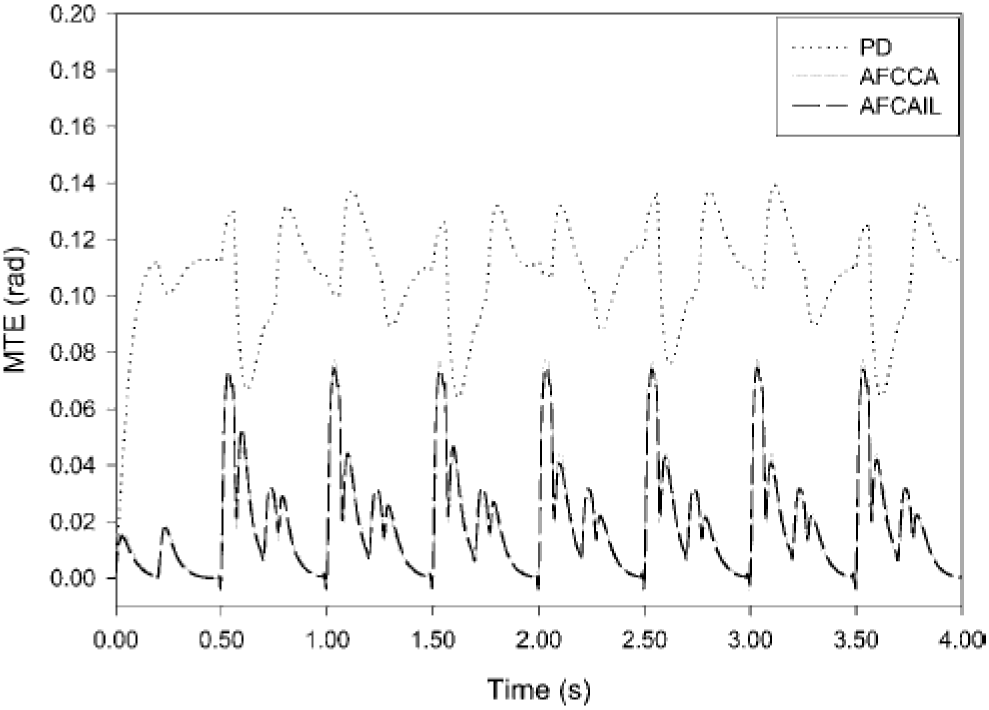


Figure 2.3: Mean tracking error generated by different control schemes with disturbances

The study by (JAHANABADI, 2011) investigates applying of Active Force Control (AFC) with Fuzzy Logic (AFCAFL) on a robotic arm that are moving by Pneumatic Artificial Muscle (PAM). The study uses fuzzy logic (FL) technique to find the optimized value of the inertia matrix in the loop of robotic arm control system. AFCPID mechanisms also play an important role to make system more effective and robustness. The Figure 2.4 below shows the comparison of PID and AFCAFL in aspect of tracking errors. AFCAFL is more stable in comparison to PID controller.

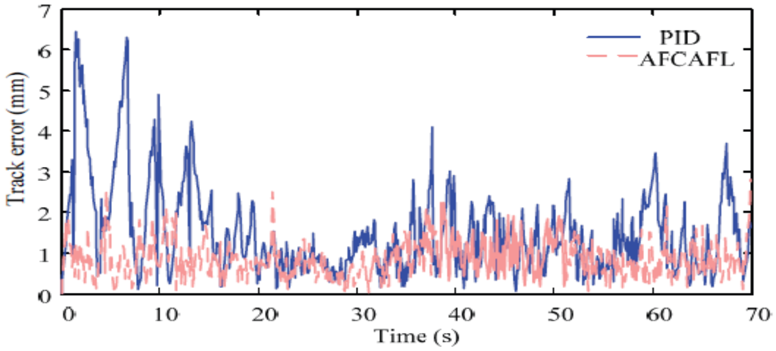


Figure 2.4: Tracking Errors

The study by (HASHEMI, 2012) proposes Active Force Control (AFC) that can reduce friction-induced vibration. The AFC based strategy reduces unwanted effect so that Friction Induced Vibration (FIV) can be decreased. Besides that, AFC based scheme also can increase the robustness of the system and reduce the vibrations of FIV system. The effect of vibration has been removed after including AFC scheme. Figure 2.5 shows that AFC is reduced the vibration better than PID controller.

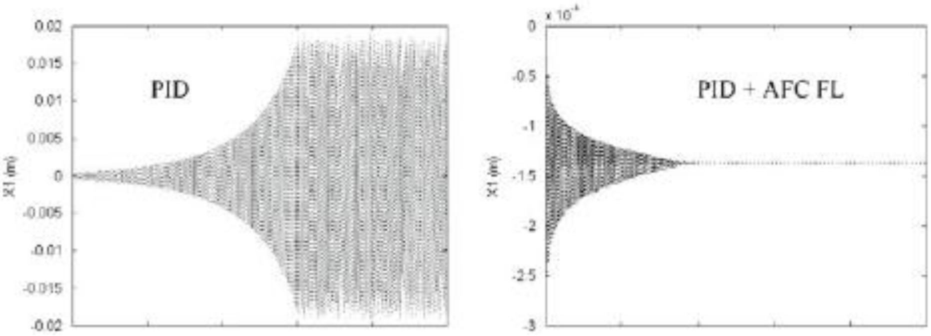


Figure 2.5: PID+AFCFL controller able stabilize the FIV system compare to PID controller alone

The study by (KOZLOWSKI, 2004) suggest to use Active Force Control for operating a mobile robot with 4 wheels together with kinematic controller based algorithm which resulted by solving both tracking and regulation problems. Tunable oscillator produces some reformed states to track some expected or unexpected signals. Many problem of system stabilization can be solved by the trajectory tracking ways and also the result can be obtained by solving the kinematic problem with the idea of a kinematic oscillator. Figure 2.6 shows trajectory tracking case.

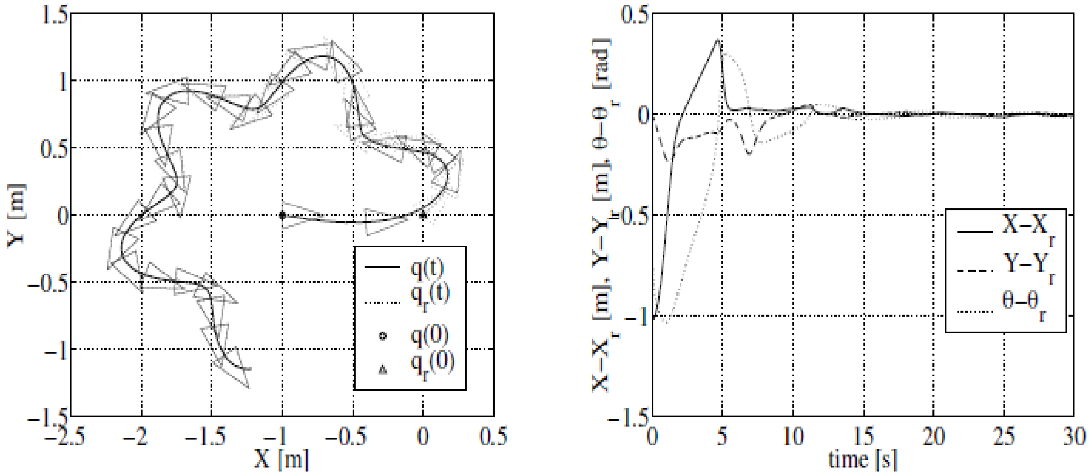


Figure 2.6: Trajectory tracking case.

The study by (HASHEM, 2015) emphasizes the mobile robot in a pre-planned path during passing through complicated environments which was tracked by a robust control algorithm. Comparison between Resolved Acceleration Control and Active Force Control has been done to test the controller capability in reducing tracking errors. The controller is evaluate the mobile robot by tracking it on the pre-defined path and at the same time eliminates the effect of the disturbances. Figure 2.8 shows the actual trajectory of controllers with disturbance.

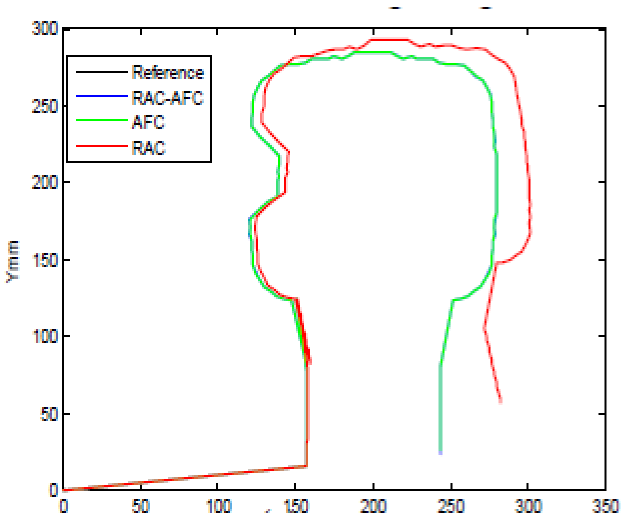


Figure 2.7: Actual trajectory of controllers with disturbance

The study by (MAILAH, 2006) emphasizes on Active Force Control effect that is led to robust and accurate performance of the non-holonomic wheeled mobile robot (WMR). AFC has influence to the trajectory tracking capability in the existence of known and unknown disturbances like irregular surface terrain, natural friction, uncertainties situation, and parametric transform. The IAFC scheme is able to cancel out all the disturbances and assure the permanence of the WMR. Figure 2.8 shows the orientation error.

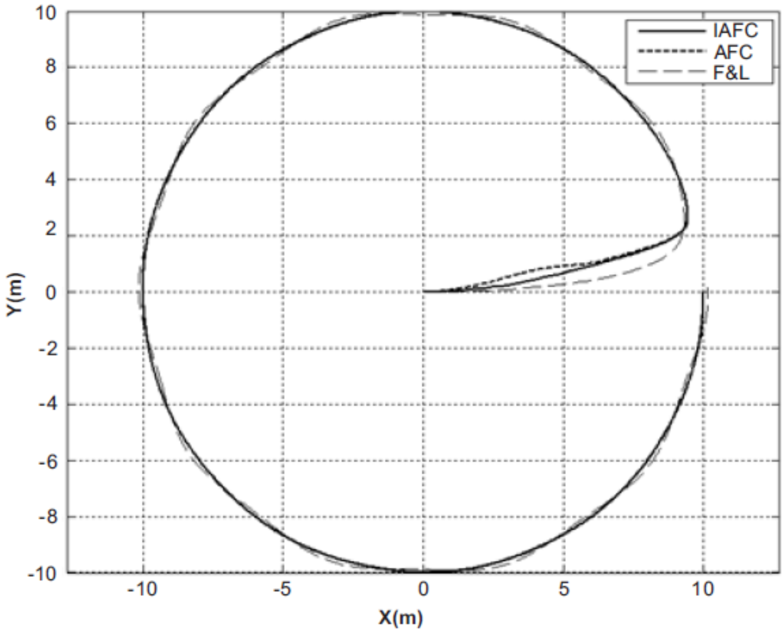


Figure 2.8: Orientation error

The study by (SHARIMAN, 2013) proposed a controller scheme for disturbance rejection in a mobile manipulator (MM) motion control based on Active Force Control (AFC). AFC scheme as shown in Figure 2.9 is able to reject the noise and disturbances and allow for faster computational time.

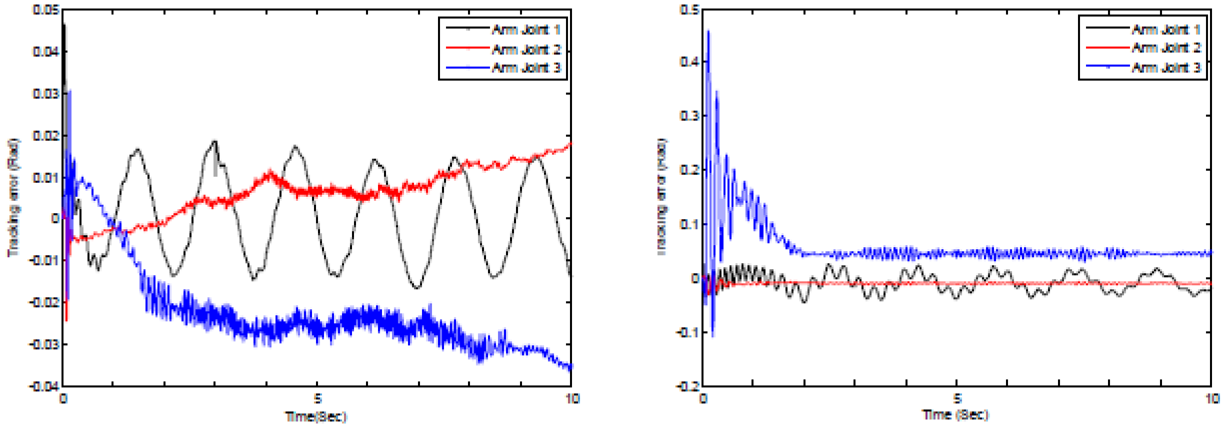


Figure 2.9: AFC-scheme more stable at arm joint 2 compare to other joint

The study by (KWEK, 2005) emphasizes implementation of evolutionary AFC strategy in 5-link biped robot that has made the system robust and stable even-though under effect of disturbances or obstacles. Figure 2.10 shows that AFCCA scheme is giving excellent trajectory tracking performance and AFC scheme demonstrates high accuracy and robustness in the biped-tracking problem.

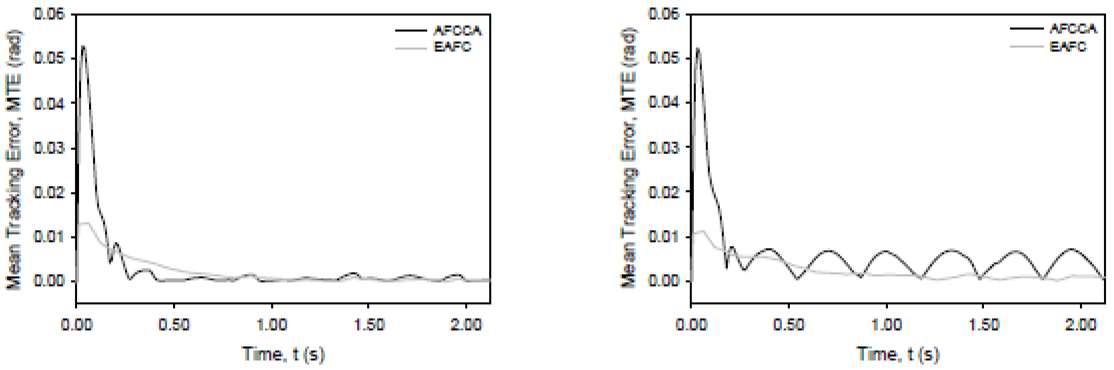


Figure 2.10: Mean tracking error generated by the biped using AFC schemes, with steady walking trajectory, (a) without disturbance, (b) with harmonic disturbances

The study by (MAILAH, 2013) emphasizes tracking performance on mobile manipulator controller based on Active Force Controller which is very robust and can eliminate all the effect of any disturbances that exist in the system. Figure 2.11 shows the AFC scheme demonstrates better noise rejection and faster in computational time compared to the computed torque controller.

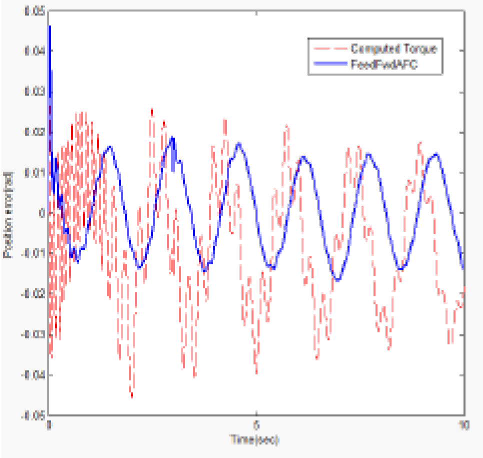


Figure 2.11: Tracking error

The study by (NURFARAHIN, 2013) emphasizes Active Force Control with Nonlinear Predictive Control which gives an excellent trajectory performance and robust against various types of known and unknown uncertainties for Five-Link Biped Model. The AFC scheme also can cancel the disturbances effects on the biped system. Table 2.1 below shows that the Nonlinear Predictive Control with Active Force Control (NPC-AFC) is more accurate and it has small value tracking error in comparison to average tracking error Nonlinear Predictive Control (NPC).

Table 2.1: Average tracking results of every joint obtained using NPC and NPC-AFC.

Average Tracking Error (deg)		
Joint	NPC	NPC-AFC
1	0.2029	0.0133
2	0.1254	0.0148
3	0.2716	0.0039
4	0.7531	0.0141

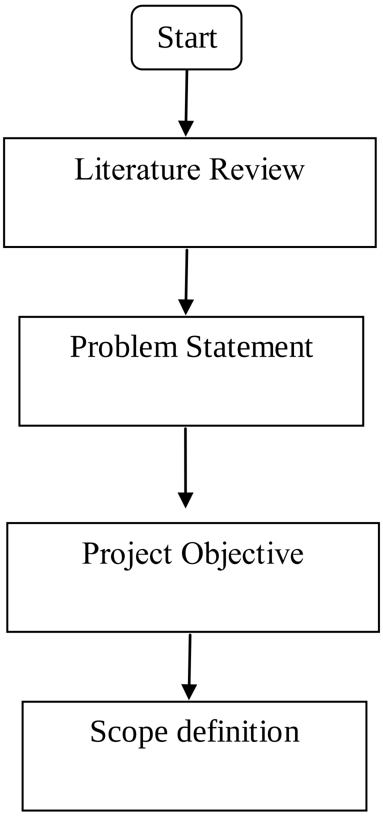
CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology plays an important role to explain the methods and instrumentation of this study. To fulfill project requirement, a flow chart is needed for describing how the process flow going on. In this study, the flow chart explains step by step of the project activities are: which is including literature review, problem statement, project objective, scope definition, proposal preparation, modeling and design, simulation of WMR, evaluation of controller, fabrication of WMR and thesis writing. The flow chart is shown as in Figure 3.1.

3.2 Flow Chart



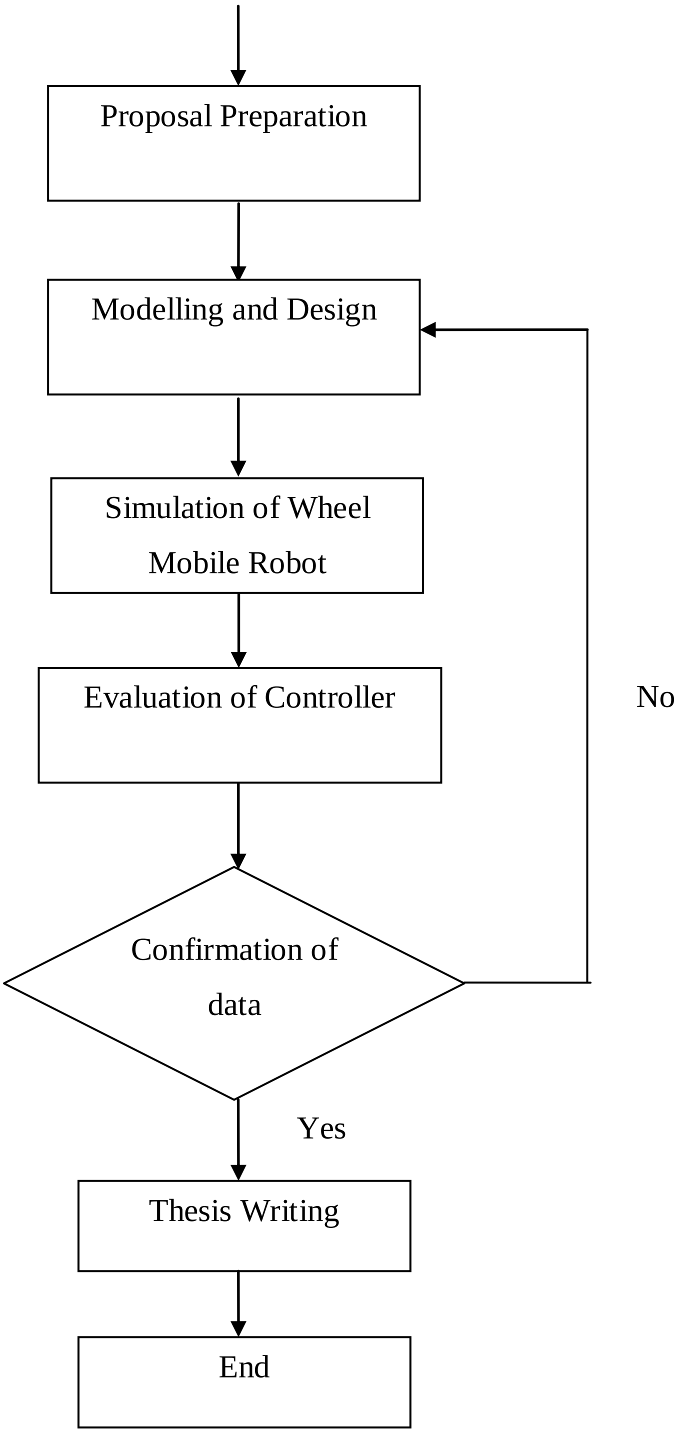


Figure 3.1: Flow chart of overall project

3.3 Literature Review

From 12 journals that are related to mobile robot control with active force control, I found that the Active Force Control is more suitable for Wheel Mobile Robot motion control. In addition, the Active Force Control is effective and has less value of tracking errors comparing with traditional controller. Besides that, an Active Force Control scheme also can keep stable or robust for a system when the mobile robot motion is moving in straight or circle paths. From the state of art, I am also trying to identify and observe strong evidence that support mobile robot motion control with using active force control to make sure that my project is going on right way.

3.4 Problem Statement

Based on literature review, it shows that Active Force Control may improve wheel mobile robot performance. Before going through anything or start doing Wheel Mobile Robot control, the problem statement is very important to address some problem that needed to be solved and come out with objective to solve the problem. In my project, it is a modeling of non-holomic Wheeled Mobile Robot and some limitation should be considered when performing simulation.

3.5 Project Objective

The main objective of this project is to model and control Wheeled Mobile Robot with three wheels using Active Force Control. Another objective of this project is to implementation Active Force Control in simulation study and also to compare the AFC scheme with other controllers like PD in circle and leaf trajectory.

3.6 Scope Definition

Basically it describes what project covers and the limitation of the Wheeled Mobile Robot. The Wheel Mobile Robot should be made of three wheels; two differential drive and castor (three degrees of freedom). In addition, each wheel always rolls on the ground without slipping (longitudinally) nor skidding (sideways) and performs active force control over the symbol path like circle or straight path.

3.7 Proposal Preparation

The proposal is including chapter 1, 2, 3, which explained title, table of contents, introduction, literature review, problem statement, objective, methodology, Gantt chart and budget plan.

3.8 Modeling and Design

The Wheeled Mobile Robot will be designed using AutoCAD. The modeling will brought me back to what I have learnt at previous semester where I will designs Active Force Control scheme using Kinematic plus dynamic equations that I have learn at 1st and 2nd year.

3.9 Simulation of Wheel Mobile Robot

For simulation path, I have developed simulation using MATLAB/simulink. The result of AFC controller in simulation should be similar as possible to the expected outcome. This path also includes the use of calculation for Wheeled Mobile Robot kinematics and dynamics.

3.10 Evaluation of Controller

Evaluation of controller is very important to complete a project. Without evaluation, the actual simulation outcome cannot be confirmed to be correct unless we compare with the reference values. The evaluation outcome should be similar to what I am expecting and it will discuss in chapter 4.

3.11 Thesis Writing

Thesis is a paperwork that describes what have been done. The thesis writing should cover overall project. The expected outcome is the Active Force Control scheme that should be stable and robust.

CHAPTER 4

MODELING AND SIMULATION OF WMR

4.1 Introduction

In this chapter, modelling and simulation of a wheeled mobile robot using MATLAB/Simulink package is presented. The goal of the simulation is to examine the performance of the WMR under the proposed control schemes involving PD controller and AFC-based systems. The main Simulink model that describes the proposed system comprises a number of components or subsystems, i.e., the PD controller, AFC loop, robot dynamic model, and others are explained relevantly in the respective sections of this chapter.

4.2 Design of Wheeled Mobile Robot

The design of WMR was developed using AutoCAD software which is shown in Figure 1.2. Wheeled Mobile Robot motion is controlled and modeled using active force controller and AutoCAD respectively. The Wheeled Mobile Robot will move using three wheels with two differential drive and one castor wheels. The motion of the Wheeled Mobile Robot can be described in global and local coordinate system as shown in Figure 1.2. Besides that, the mobile robot motion control has some limitation due to each wheel is assumed to be rolled on the ground without slipping (longitudinally) nor skidding (sideways).

4.3 Kinematic Model

The mobile robot is moving using two differential drive and castor wheels. The velocity of each wheel can be founded by Equations (4.1) and (4.2):

$$\text{Velocity right wheel, } V_r = r\,\dot{\theta}_r \tag{4.1}$$

$$\text{Velocity left wheel, } V_l = r\,\dot{\theta}_l \tag{4.2}$$

Thus, the velocity of mobile robot is a combination of velocity right wheel and left wheel. Therefore, the velocity of mobile robot can be illustrated in Equation (4.3):

$$\text{Velocity of mobile robot, } V = \frac{V_r + V}{2} = \frac{r\,\dot{\theta}r + r\,\dot{\theta}}{2} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta} \end{bmatrix} \tag{4.3}$$

The difference between angular velocity of right and left wheels can be written in relation with heading rotation angle which is shown in Equation (4.4):

$$\dot{\varphi} = \frac{V_r + V}{2b} = \frac{r\,\dot{\theta}r - r\,\dot{\theta}}{2b} = \begin{bmatrix} \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta} \end{bmatrix} \tag{4.4}$$

Local coordinate system can be written as shown in Equation (4.5):

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos(\varphi) & -d\sin(\varphi) \\ \sin(\varphi) & d\cos(\varphi) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \dot{\varphi} \end{bmatrix}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos(\varphi) & -d\sin(\varphi) \\ \sin(\varphi) & d\cos(\varphi) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{r\,\dot{\theta}r + r\,\dot{\theta}}{2} \\ \frac{r\,\dot{\theta}r - r\,\dot{\theta}}{2b} \end{bmatrix} \tag{4.5}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{r\cos(\varphi)\dot{\theta}r + r\cos(\varphi)\,\dot{\theta}}{2} & \frac{-dr\sin(\varphi)\,\dot{\theta}r + dr\sin(\varphi)\dot{\theta}}{2b} \\ \frac{r\sin(\varphi)\dot{\theta}r + r\sin(\varphi)\,\dot{\theta}}{2} & \frac{dr\cos(\varphi)\,\dot{\theta}r - dr\cos(\varphi)\dot{\theta}}{2b} \\ 0 & \frac{r\,\dot{\theta}r - r\,\dot{\theta}}{2b} \end{bmatrix}$$

Then, Equation (4.5) can be written as Equation (4.6) in means of angular velocity $\dot{\theta}_r$ and $\dot{\theta}$:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos(\varphi) - \frac{dr}{2b}\sin(\varphi) & \frac{r}{2}\cos(\varphi) + \frac{dr}{2b}\sin(\varphi) \\ \frac{r}{2}\sin(\varphi) + \frac{dr}{2b}\cos(\varphi) & \frac{r}{2}\sin(\varphi) - \frac{dr}{2b}\cos(\varphi) \\ \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta} \end{bmatrix} \tag{4.6}$$

In a short abbreviation Equation (4.6) can be written in Equation (4.7):

$$\dot{q} = S^T(\varphi)\dot{\theta} \tag{4.7}$$

4.4 Dynamic Model

The dynamics of mobile robot can be derived using Lagrange equation in Equation (4.8):

$$\frac{\delta}{dt}\frac{\delta k}{\delta_{qi}} - \frac{\delta k}{\delta_{qi}} = \tau_i - A^T(q)\,\lambda \tag{4.8}$$

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 body can be described as Equation (4.9):

$$\mathrm{KE}_{\mathrm{body}} = \frac{1}{2}m_r(\dot{x}^2 + \dot{y}^2) + \frac{1}{2}I_r\dot{\varphi}^2 \tag{4.9}$$

It also can be written after derivation:

$$\frac{\delta k}{\delta_{qi}} = \frac{1}{2}m_r 2\ddot{x} + \frac{1}{2}m_r 2\ddot{y} + \frac{1}{2}I_r 2\ddot{\varphi} \tag{4.10}$$

$$\frac{\delta}{dt}\frac{\delta k}{\delta_{qi}} = m_r\ddot{x} + m_r\ddot{y} + I_r\ddot{\varphi} \tag{4.11}$$

The kinematic energy of the right wheel can be described as in Equation (4.12):

$$\mathrm{KE}_{\mathrm{rw}} = \frac{1}{2}m_w(\dot{x} + b\dot{\varphi}\cos(\varphi) + d\dot{\varphi}\sin(\varphi))^2 + \frac{1}{2}m_w(\dot{y} + b\dot{\varphi}\sin(\varphi) - d\dot{\varphi}\cos(\varphi))^2 + \frac{1}{2}I_w\dot{\varphi}^2 + \frac{1}{2}I_w\dot{\theta}_r^2 \tag{4.12}$$

The kinematic energy of the left wheel can be described Equation (4.13):

$$\mathrm{KE}_{\mathrm{lw}} = \frac{1}{2}m_w(\dot{x} - b\dot{\varphi}\cos(\varphi) + d\dot{\varphi}\sin(\varphi))^2 + \frac{1}{2}m_w(\dot{y} - b\dot{\varphi}\sin(\varphi) - d\dot{\varphi}\cos(\varphi))^2$$

$$+\ \frac{1}{2} I_w \dot{\varphi}^{\,2} + \frac{1}{2} I_w \dot{\theta}^{\,2} \tag{4.13}$$

The dynamic equation of mobile robot motion system can be written as in Equation (4.14):

$$\mathrm{m}\ddot{x}_c + K(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi) - \lambda_1 \sin\varphi - \cos\varphi\,(\lambda_2 + \lambda_3) = 0,$$

$$\mathrm{m}\ddot{y}_c - K(\ddot{\varphi}\cos\varphi - \dot{\varphi}^2\sin\varphi) + \lambda_1 \cos\varphi - \sin\varphi\,(\lambda_2 + \lambda_3) = 0,$$

$$I\ddot{\varphi} + K(\ddot{x}_c \sin\varphi - \ddot{y}_c \cos\varphi) - d\lambda_1 + b(\lambda_3 - \lambda_2) = 0,$$

$$I_w\ddot{\theta}_r + \lambda_2\, r = \tau_r\ , \tag{4.14}$$

$$I_w\ddot{\theta}\ + \lambda_3\, r = \tau\ \ ,$$

where,

$\mathrm{m} = m_p + 2m_w$,
$K = \left(2m_w d - m_p\Delta\right),$
$I = I_p + m_p\Delta^2 + 2m_w(b^2 + d^2) + 2I_m$ [4.13]

Therefore, by deriving Equations (4.14), the Lagrange Equation can be written in Equation (4.15):

$$\mathrm{M(q)}\ddot{q} + V(q, \dot{q}) = E(q)\tau \tag{4.15}$$

where:

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

$$V(q,\dot{q}) = \begin{bmatrix} 2m_w d\dot{\varphi}^2 \sin(\varphi) \\ 2m_w d\dot{\varphi}^2 \cos(\varphi) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$E(q) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\tau = \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix}$$

$$\ddot{q} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\varphi} \\ \ddot{\theta}_r \\ \ddot{\theta}_l \end{bmatrix}$$

τ : Non-conservative applied force

M (q): Positive definite inertia matrix

V (q,$\dot{q}$): Centripetal and Coriolis matrix

E(q): Input transformation matrix

4.5 Design of Controller

The path of mobile robot is controlled using Proportional–derivative controller, Active Force Control and combination strategy that implement PD and AFC together as shown in Figure 1.1.

4.5.1 PD Control Strategies

This controller operates based on kinematic parameters and it can be used to minimize position and direction errors during path control. This controller is used as reference value for Active Force Control scheme after multiply by estimated inertia matrix. Equation (4.16-4.18) shows the design of his PD controller.

$$\dot{x}_{error} = \left(\dot{x}_{ref} - \dot{x}_{act}\right)[\ k_p\ ] + [\ k_d][\frac{d_{\dot{x}_{ref} - \dot{x}_{act}}}{d_t}\ ] \tag{4.16}$$

$$\dot{y}_{error} = \left(\dot{y}_{ref} - \dot{y}_{act}\right)[\ k_p\ ] + [\ k_d][\frac{d_{\dot{y}_{ref} - \dot{y}_{act}}}{d_t}\ ] \tag{4.17}$$

$$\dot{\varphi}_{error} = \left(\dot{\varphi}_{ref} - \dot{\varphi}_{act}\right)[\ k_p\ ] + [\ k_d][\frac{d_{\dot{\varphi}_{ref} - \dot{\varphi}_{act}}}{d_t}\ ] \tag{4.18}$$

Subscripts references refer to the input values and the subscripts actual refer to the output values. The comparison between reference and actual can evaluate the stability of the control system. The smaller the tracking error, the better the motion control of a mobile robot. k_p is a proportional gains and it can be obtained by multiply an estimated value chosen arbiter using try-error method. k_d is a differential gain which can be obtained by multiply $\frac{d_u}{d_t}$ with an estimated value chosen arbiter using try-error method. Figure 4.1 and 4.2 shows PD controller with and without disturbances respectively.

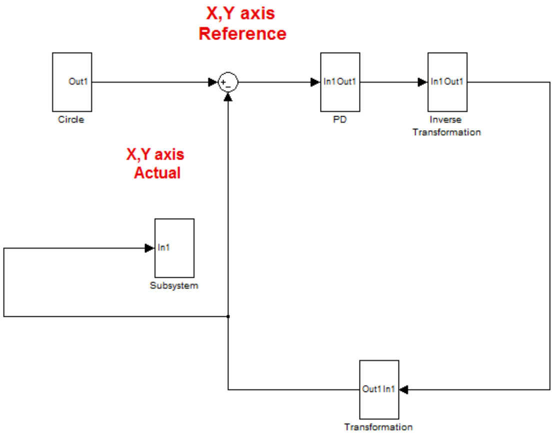


Figure 4.1: PD controller (without disturbances)

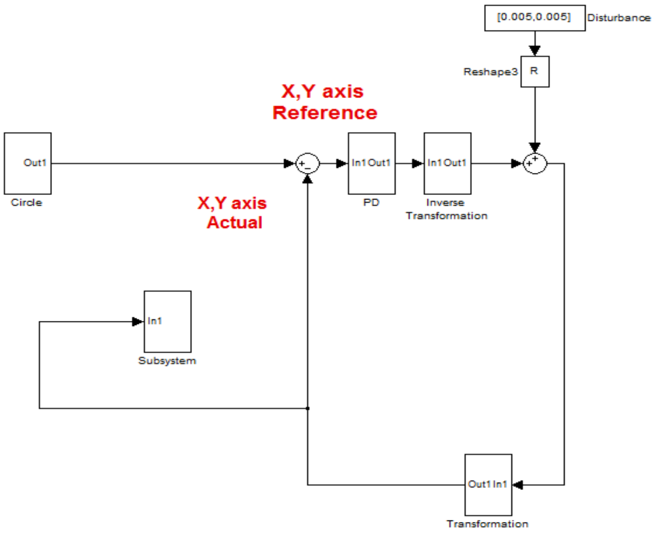


Figure 4.2: PD controller (with disturbances)

4.5.2 AFC Control Strategy

This controller is an inner loop of PD-AFC controller which depends on the angular acceleration of the wheels and Inertia Matrix IN. IN is very important in the AFC strategy and needs to be estimated using Artificial Methods. Fuzzy Logic Toolbox (FL) has been chosen for estimating the inertia matrix because it is simple and functional in comparison with other method. From (MUSA MAILAH, 2006), it can be found that AFC control strategy works effectively if the minimum and maximum values of IN is chosen between 0.4M < IN < 0.12M. IN plays a important role in determining the estimated torque disturbance, τ_d^*. The measurement of acceleration with estimated Inertia Matrix will be compared with applied torque to estimate torque disturbance which can be written as in Equation (2.1). Figure 4.3 and 4.5 shows AFC controller with and without disturbances respectively. Figure 4.4 and 4.6 shows PD-AFC controller with and without disturbances respectively.

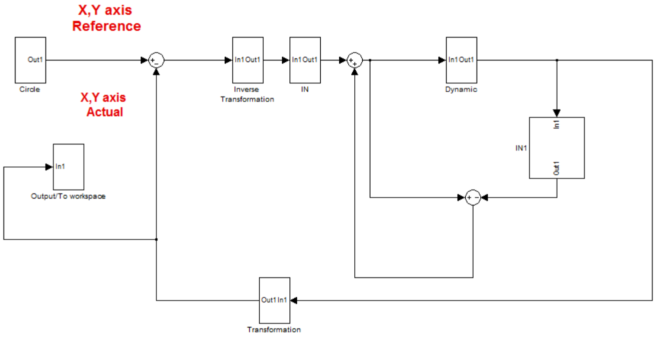


Figure 4.3: AFC controller (without disturbances)

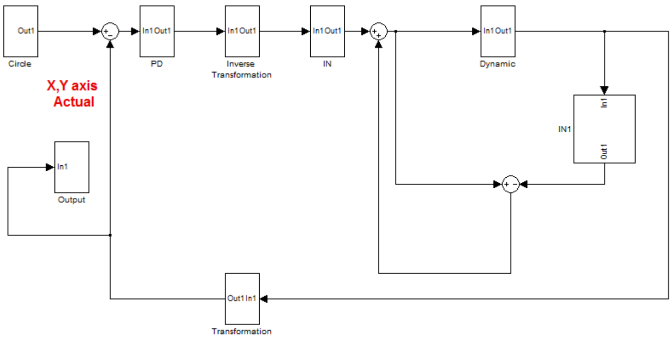


Figure 4.4: PDAFC controller (without disturbances)

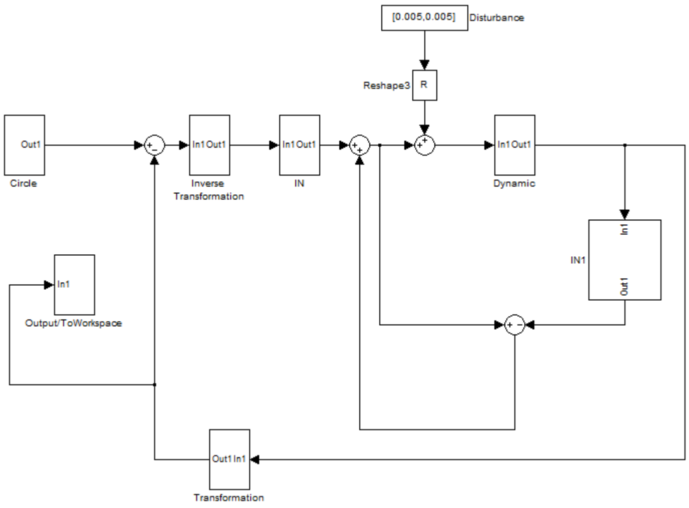


Figure 4.5: AFC controller (with disturbances)

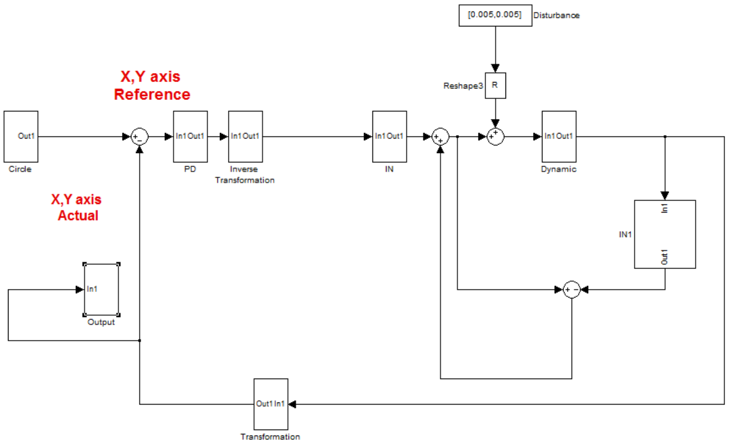


Figure 4.6: PDAFC controller (with disturbances)

4.6 Estimated Inertia Matrix

In estimated Inertia Matrix, the heading rotation φ is used as the input of Fuzzy Logic Toolbox which has the following fuzzy set variables {Very Small, Small, Medium, Large, and Very Large} as shown in Figure 4.7. Then, the output of Fuzzy Logic Toolbox has two variables which are Inertia Matrix for right (INR) and left wheels (INL) as shown in Figure 4.8 and Figure 4.9. Both INR and INL have fuzzy set with variables {Very small, Small, Medium, Large and Very Large}. Moreover, the five simple fuzzy rules are designed in IF-Then structure that is creating inside Fuzzy Logic Toolbox as shown in Table 4.1. From equation (2.1), INR and INL have to be chosen between 0.12kg.m^2 and 0.36 kg.m^2.

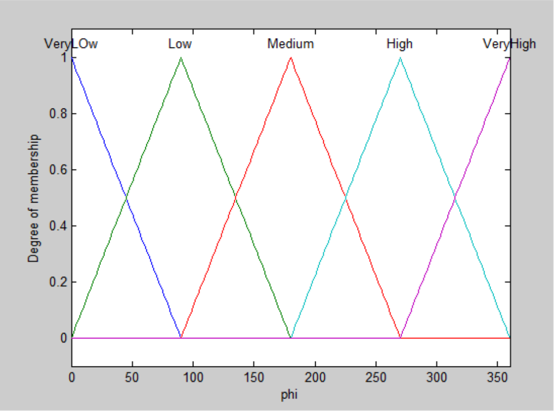


Figure 4.7: Degree membership of input, φ

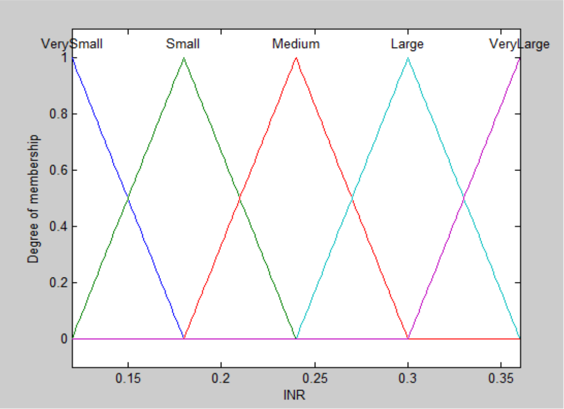


Figure 4.8: Degree membership of output for right wheel, INR

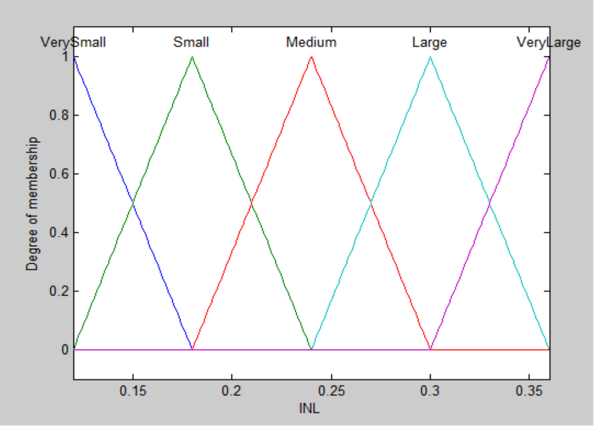


Figure 4.9: Degree membership of output for left wheel, INL

Table 4.1 shows the output INR and INL has the relation with phi as illustrated in the following IF-THEN structure rules.

Table 4.1: Five simple fuzzy rules which designed in IF-Then structure

1. If phi is Medium then INR is Medium and INL is Medium.
2. If phi is Very Small then INR is Very Small and INL is Very Large.
3. If phi is Small then INR is Small and INL is Large.
4. If phi is Large then INR is Large and INL is Small.
5. If phi is Very Large the INR is Very Large and INL is Very Small.

4.7 Simulation Setup

The simulation is performed using MATLAB/SIMULINK. SIMULINK is a block diagram environment that I can use to design mobile robot motion controller model. Firstly I have set up the configuration parameter & simulink model. Then I used many functions to import and export parameters to workspace settings in order to make model runs smoothly. After that, I can evaluate and analyze my Active Force Controller.

Configuration Parameter:	Simulation time – Start from 0 s until 360 seconds Solver - Fixed-step with ODE3 Auto fixed step

Wheel Mobile Robot Parameter:

r=0.1m, b=0.02m, d=0.5m, m=36kg,
m_w = 0.8kg, I = 18 kg.m^2, I_w = 0.00818 kg.m^2,
Disturbance = [0.005 0.005]N.m

Controller Parameter:

Kp for x,y and φ = 0.98
Kd for x,y and φ = 0.005

Figure 4.10 shows the mask of PD controller

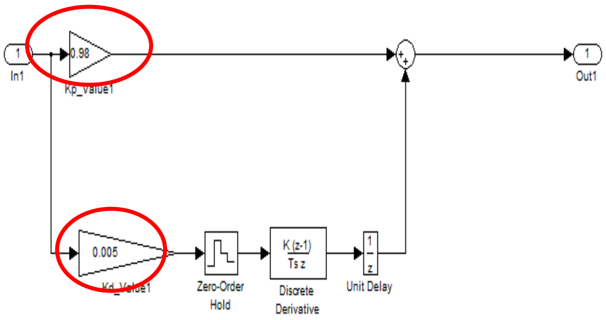


Figure 4.10: K_p and K_d values

4.8 Kinematic Model Implementation in MATLAB/ Simulink

The Figure 4.11 is Simulink model of an AFC controller. Figure 4.11 is described the location of kinematic model subsystem for both system with/ without disturbances. Then, the inverse of kinematic system is used to convert from global coordinate system (x, y,φ) to local coordinate system (θ_r, θ_l) which is highlighted as mask in Figure 4.12. Wheel mobile robot parameter are: r=0.1m, b=0.02m, d=0.5m and m=36kg.

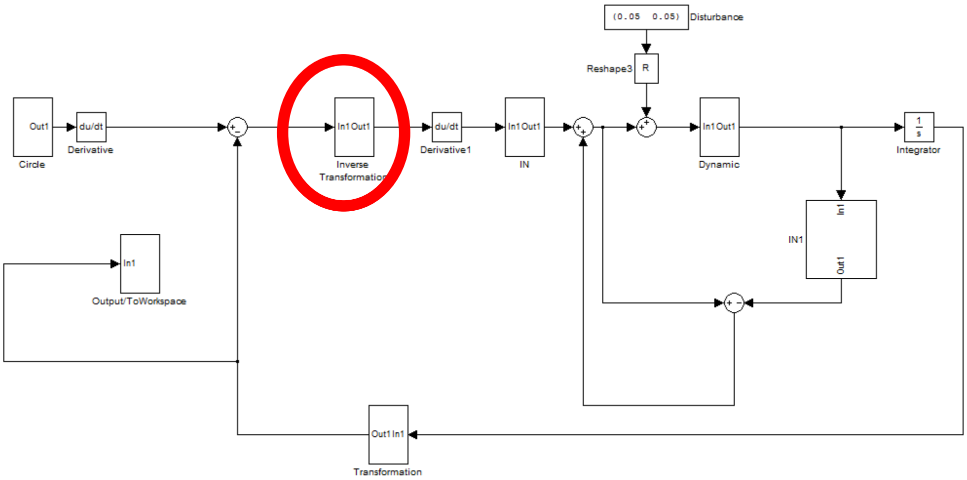


Figure 4.11: Location of Kinematic model

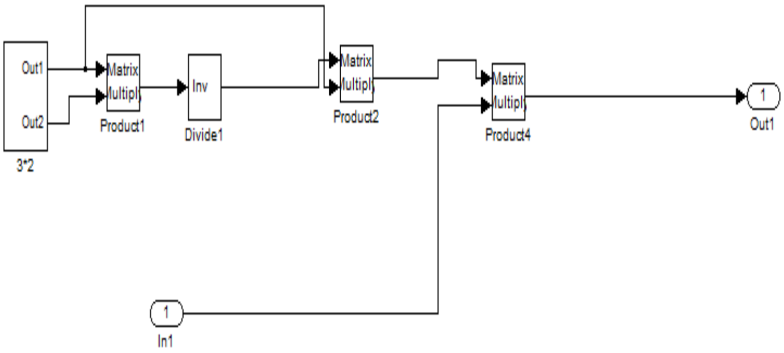


Figure 4.12: Look under mask

Figure 4.2.13 to Figure 4.2.19 described the equation (4.6) :

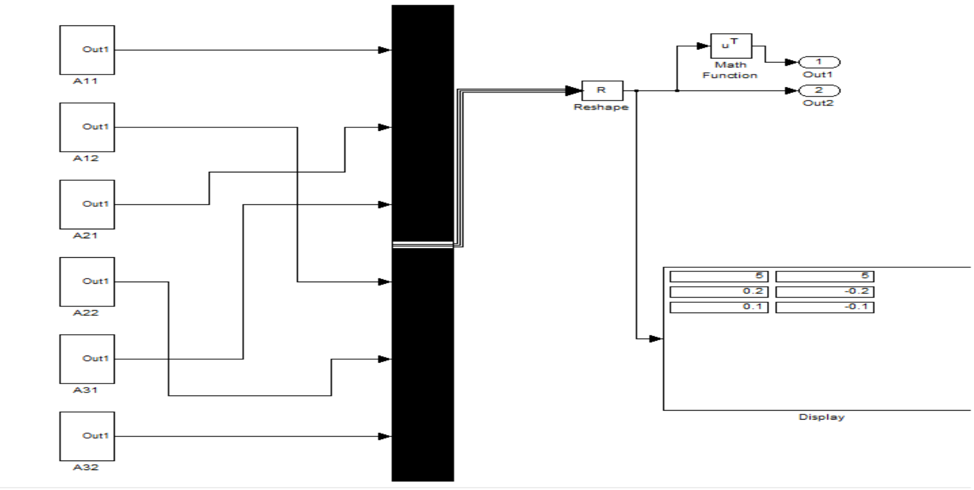


Figure 4.13: Kinematic model equation (4.6)

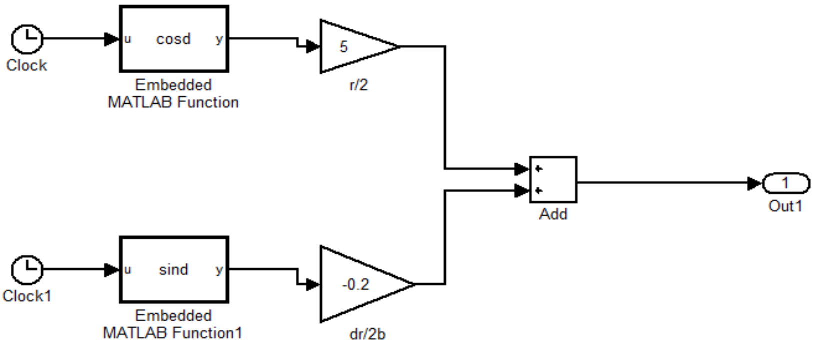


Figure 4.14: Equation $\frac{r}{2}\cos(\varphi) - \frac{dr}{2b}\sin(\varphi)$

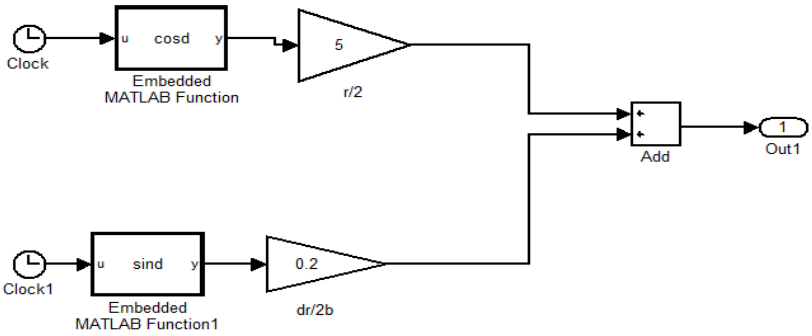


Figure 4.15: Equation $\frac{r}{2}\cos(\varphi) + \frac{dr}{2b}\sin(\varphi)$

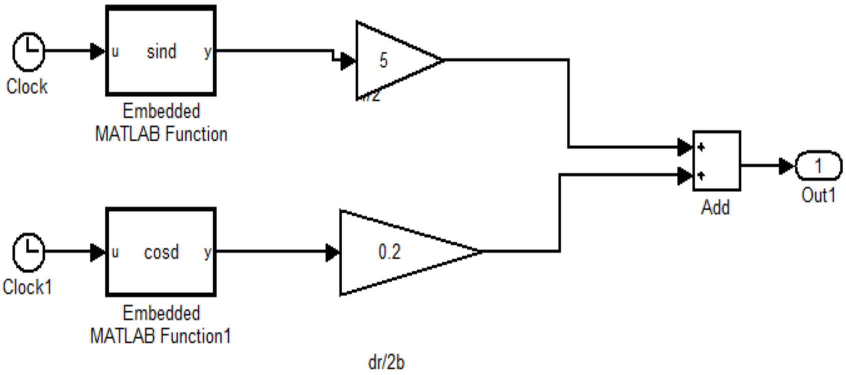


Figure 4.16: Equation $\frac{r}{2}\sin(\varphi) + \frac{dr}{2b}\cos(\varphi)$

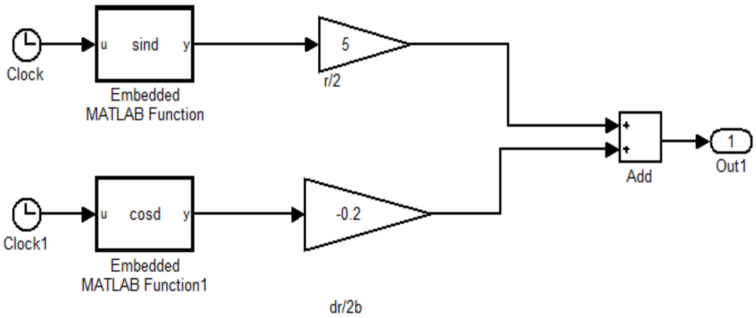


Figure 4.17: Equation $\frac{r}{2}\sin(\varphi) - \frac{dr}{2b}\cos(\varphi)$

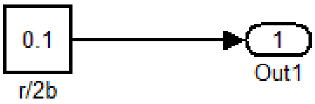


Figure 4.18: Equation $\frac{r}{2b}$

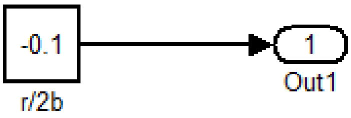


Figure 19: Equation $-\frac{r}{2b}$

Figure 4.20 described inverse which can be determined by: (B) = BT*((B*BT) ^-1).

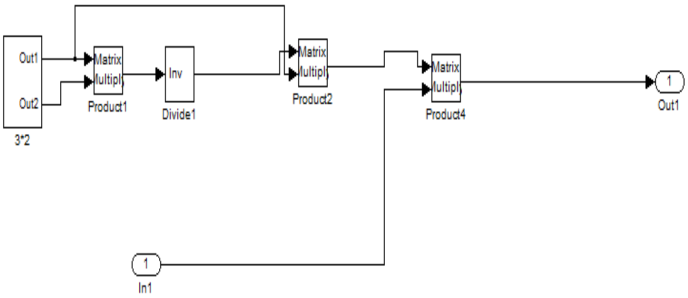
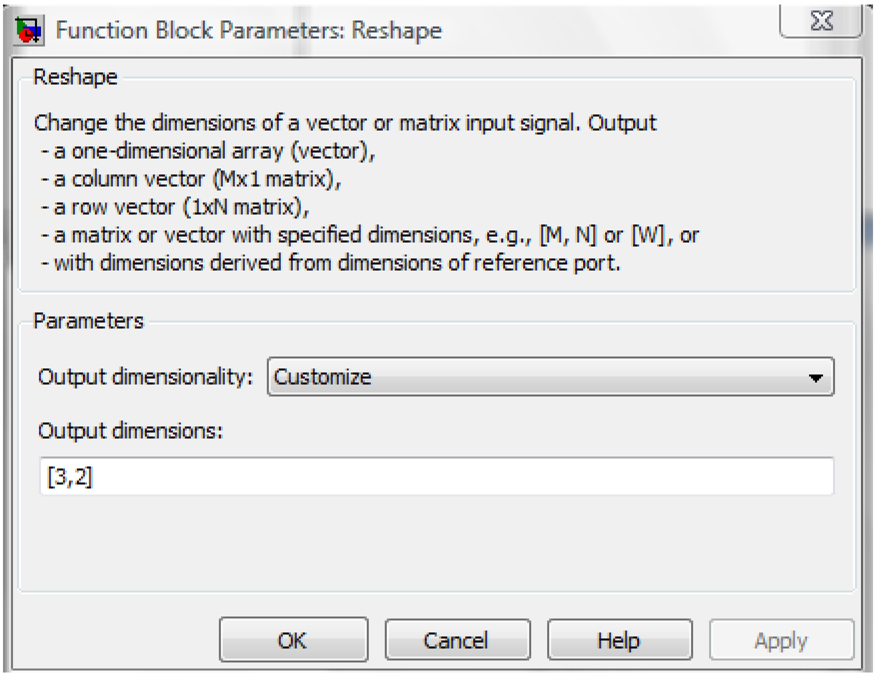


Figure 4.20: Inverse

Figure 4.21 shows that how the setting of reshape block which can setting the format of matrix.


Function Block Parameters: Reshape

Reshape

Change the dimensions of a vector or matrix input signal. Output
- a one-dimensional array (vector),
- a column vector (Mx1 matrix),
- a row vector (1xN matrix),
- a matrix or vector with specified dimensions, e.g., [M, N] or [W], or
- with dimensions derived from dimensions of reference port.

Parameters

Output dimensionality: Customize

Output dimensions:

[3,2]

Figure 4.21: Setting of Reshape Block

4.9 Dynamic Model Implementation in Matlab Simulink

The Figure 4.22 is Simulink model of an AFC controller for both with/ without disturbances systems. Figure 4.22 is described the location of dynamic model subsystem. Figure 4.23 and Figure 4.24 are described multiple and add block. Wheel mobile robot parameter are r=0.1m, b=0.02m, d=0.5m, m=36kg, $m_w = 0.8$kg, I = 18 kg.m^2 and $I_w =$ 0.00818 kg.m^2 .

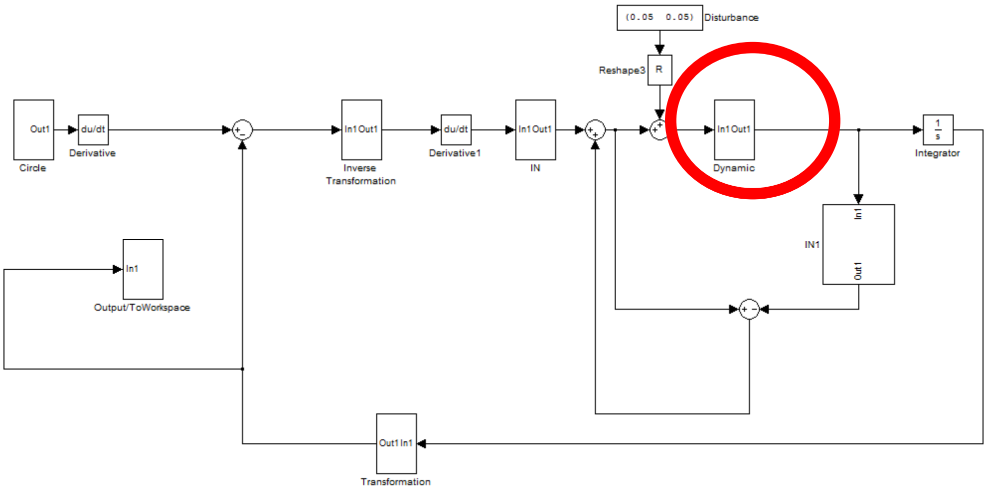


Figure 4.22: Location of Dynamic model

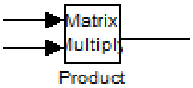


Figure 4.23: Multiple of two input matrix value

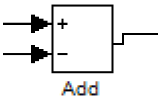


Figure 4.24: Add of two input

Figure 4.25 to Figure 4.33 described the equation (4.15) :

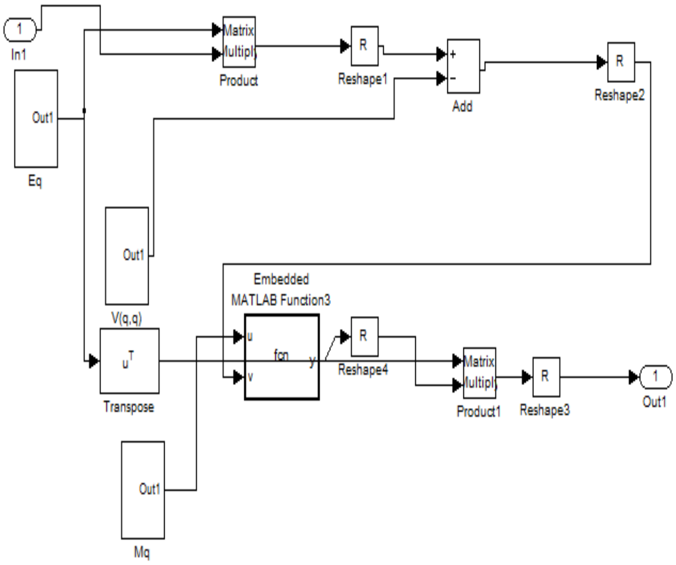


Figure 4.25: Dynamic model equation (4.15)

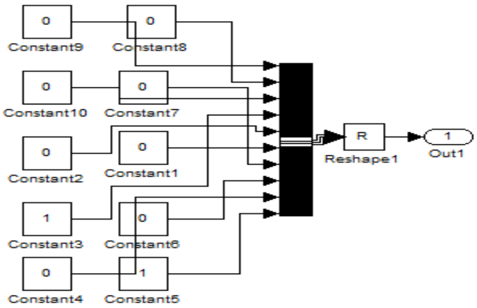


Figure 4.26: Matrix of E (q)

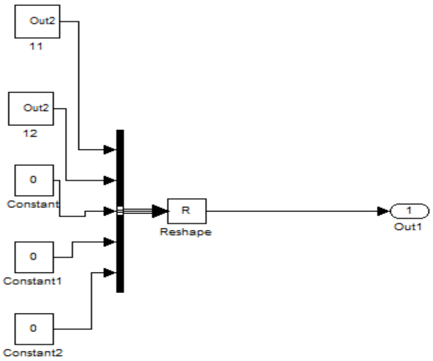


Figure 4.27: Matrix of V (q, q̇)

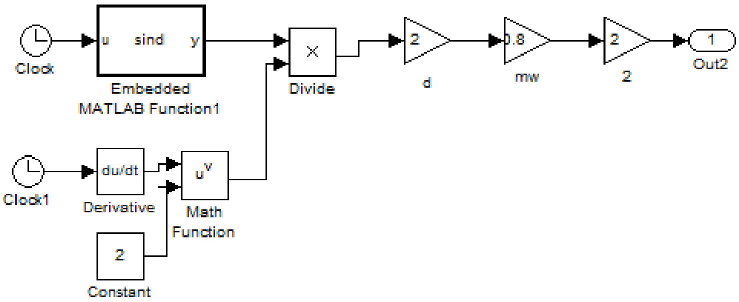


Figure 4.28: Equation $2m_w d\dot{\varphi}^2 \sin(\varphi)$

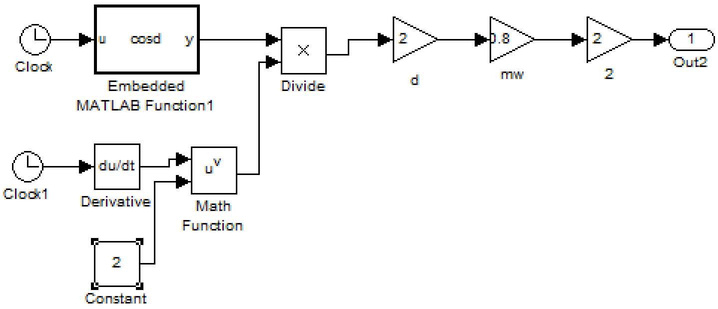


Figure 4.29: Equation $2m_w d\dot{\varphi}^2 \cos(\varphi)$

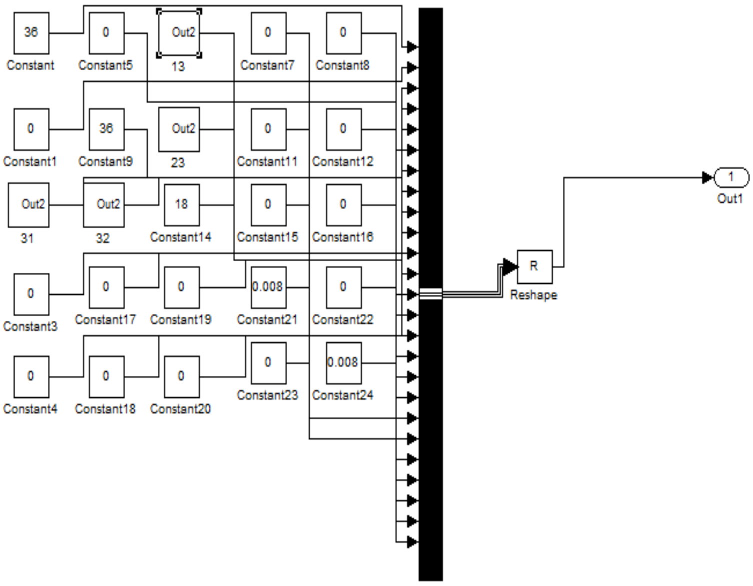


Figure 4.30: Matrix of M (q)

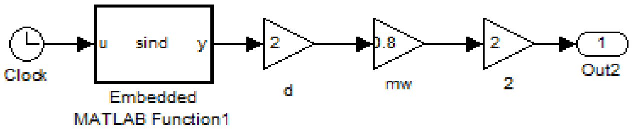


Figure 4.31: Equation $2m_w d \sin(\varphi)$

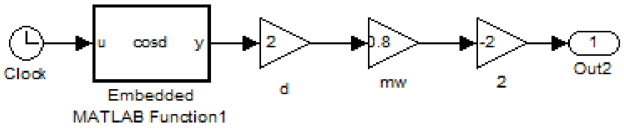


Figure 4.32: Equation $-2m_w d \cos(\varphi)$

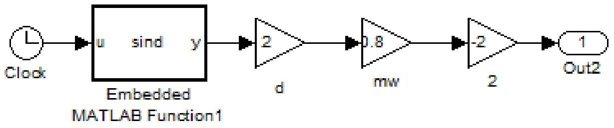


Figure 4.33: Equation $-2m_w d \sin(\varphi)$

4.10 Evaluation of Controller

The evaluation of controllers will be accomplished using Average Tracking Errors method:

4.10.1 Percentage of Average Tracking Error

The simulation results can be indicated more clearly if we find out the values of average tracking errors. After simulation is run in MATLAB/ simulink, the output value sent to MATLAB workspace by using To Workspace Blok which shown in Figure 4.34. Then the value of average track errors can be found at MATLAB workspace which shown in Figure 4.35. After that, I plot a graph or table from the value of MATLAB workspace which shown in Figure 4.36. Finally, the percentage of average tracking errors are taken by comparing the reference value with the actual value in Table 5.1, 5.3, 5.6, 5.8 (without disturbances) and Table 5.2, 5.4, 5.7, 5.9 (with disturbances).

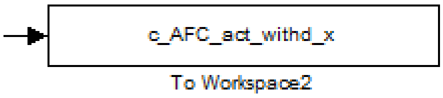
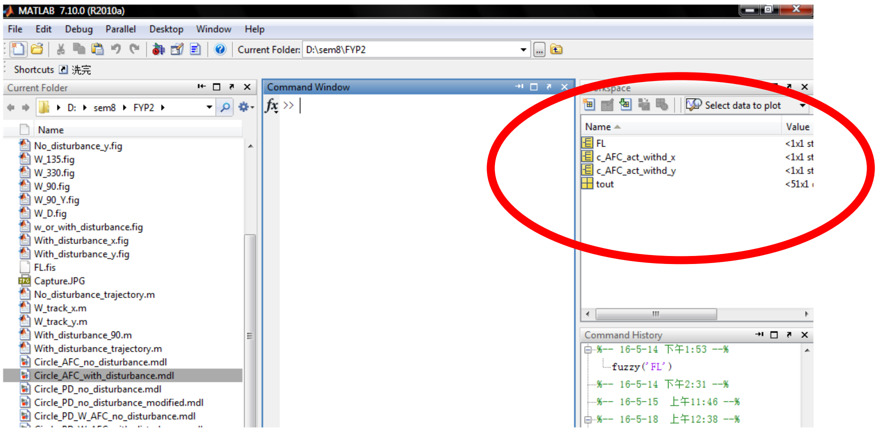


Figure 4.34: To Workspace Blok

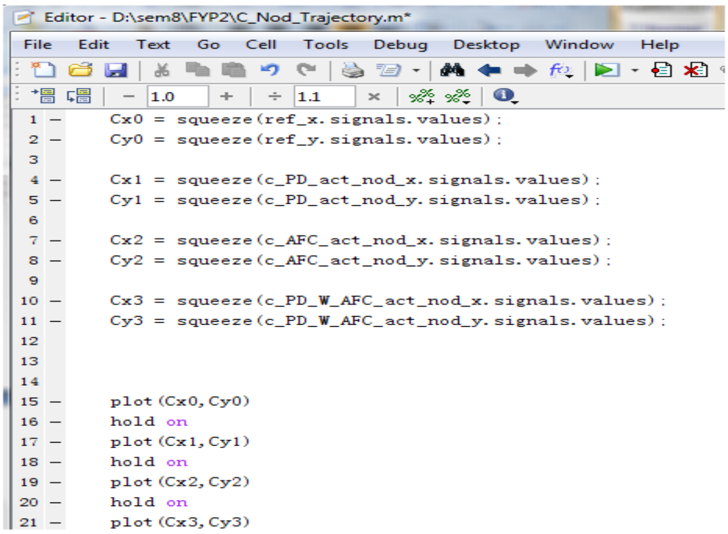


Name	Value
FL	<1x1 st
c_AFC_act_withd_x	<1x1 st
c_AFC_act_withd_y	<1x1 st
tout	<51x1

```
%-- 16-5-14 下午1:53 --%
fuzzy('FL')
%-- 16-5-14 下午2:31 --%
%-- 16-5-15 上午11:46 --%
%-- 16-5-18 上午12:38 --%
```

Figure 4.35: Location of MATLAB Workspace

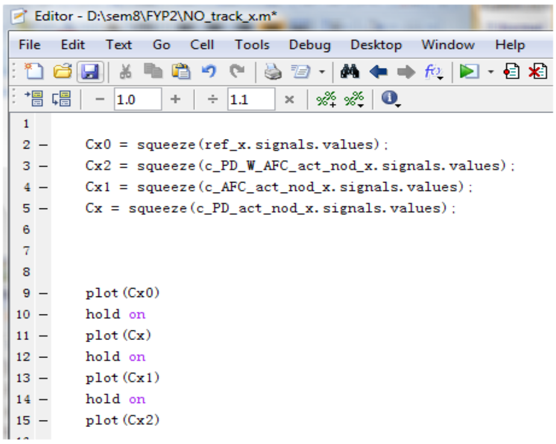
Figure 4.36 described a coding in MATLAB Editor for plotting Trajectory.



```
Cx0 = squeeze(ref_x.signals.values);
Cy0 = squeeze(ref_y.signals.values);

Cx1 = squeeze(c_PD_act_nod_x.signals.values);
Cy1 = squeeze(c_PD_act_nod_y.signals.values);

Cx2 = squeeze(c_AFC_act_nod_x.signals.values);
Cy2 = squeeze(c_AFC_act_nod_y.signals.values);

Cx3 = squeeze(c_PD_W_AFC_act_nod_x.signals.values);
Cy3 = squeeze(c_PD_W_AFC_act_nod_y.signals.values);



plot(Cx0,Cy0)
hold on
plot(Cx1,Cy1)
hold on
plot(Cx2,Cy2)
hold on
plot(Cx3,Cy3)
```

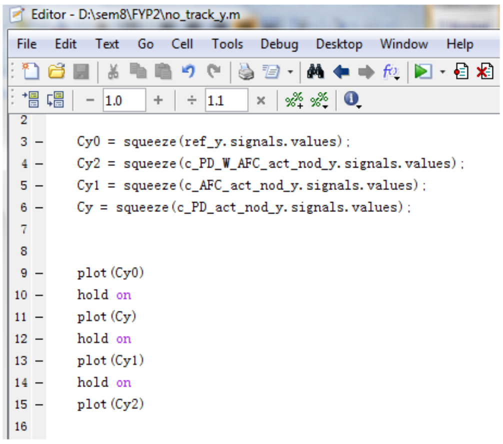
Figure 4.36: MATLAB Editor for Trajectory

Figure 4.37 and Figure 4.38 describe the coding in MATLAB Editor for plotting track x and track y respectively.



```

Cx0 = squeeze(ref_x.signals.values);
Cx2 = squeeze(c_PD_W_AFC_act_nod_x.signals.values);
Cx1 = squeeze(c_AFC_act_nod_x.signals.values);
Cx = squeeze(c_PD_act_nod_x.signals.values);



plot(Cx0)
hold on
plot(Cx)
hold on
plot(Cx1)
hold on
plot(Cx2)
```

Figure 4.37: MATLAB Editor for track error x



```

Cy0 = squeeze(ref_y.signals.values);
Cy2 = squeeze(c_PD_W_AFC_act_nod_y.signals.values);
Cy1 = squeeze(c_AFC_act_nod_y.signals.values);
Cy = squeeze(c_PD_act_nod_y.signals.values);



plot(Cy0)
hold on
plot(Cy)
hold on
plot(Cy1)
hold on
plot(Cy2)

```

Figure 4.38: MATLAB Editor for track error y

CHAPTER 5

RESULT AND DISCUSSION

5.1 Introduction

The simulation is evaluating using MATLAB / Simulink. The evaluation of controller was divided into two groups: one with disturbances and another group without disturbances. They are three controllers in each group; namely are PD, AFC and PDAFC controllers.

5.2 Tracking Errors of Circle

Figure 5.2 until Figure 5.7 describes the comparison between three different control methods which are PD, AFC and PDAFC controllers in terms of stabilization of the wheel mobile robot. Figure 5.2 and Figure 5.3 show the comparison in trajectory tracking errors. Figure 5.4 and Figure 5.5 show track errors in x-axis. Figure 5.6 and Figure 5.7 show track errors in y-axis. There were almost similar diagram because trajectory tracking errors are very small among three controllers since all the controller are steady in motion control in the case of no disturbances condition which is described at Figure 5.2, Figure 5.4 and Figure 5.6. From Figure 5.3, Figure 5.5 and Figure 5.7, it can be observed and concluded that PD controller has big different value comparing with reference value. PD controller is become ineffective when disturbances are applying to the controller. AFC controller is unchangeable which means no big different with reference values, tracking errors in AFC are very small and overlapped the reference diagram. Figure 5.0 below shows reference and actual ideal for Circle.

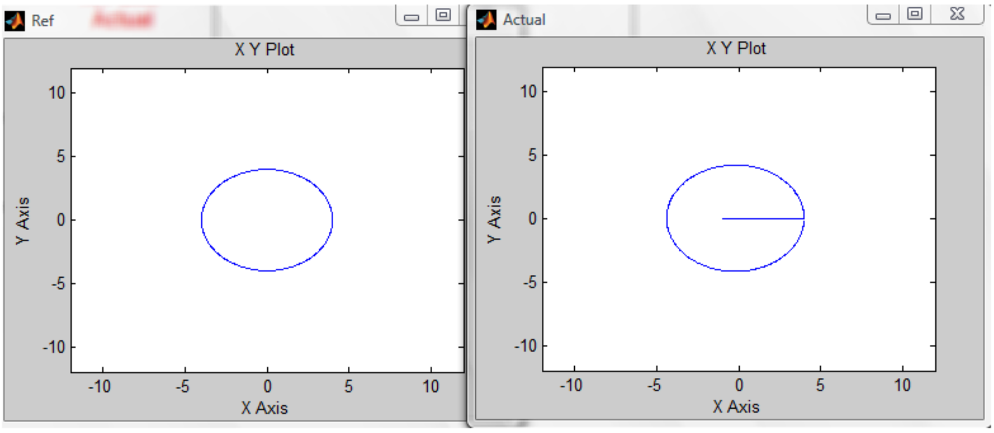


Figure 5.1: Reference and Actual Diagram

Figure 5.2 and Figure 5.3 show the comparison in trajectory tracking errors.

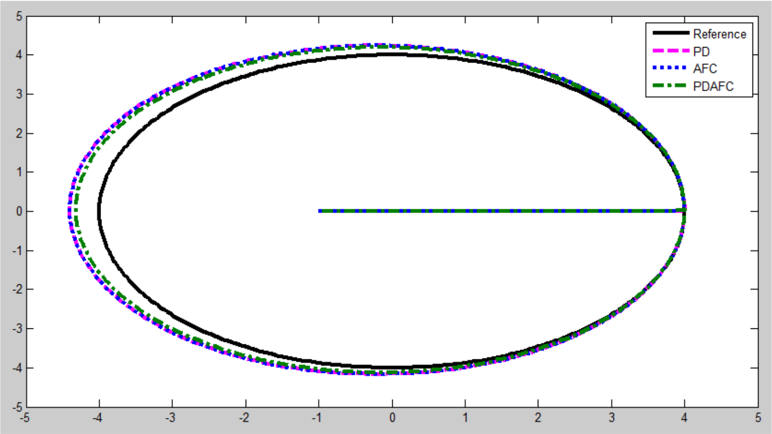


Figure 5.2: Trajectory tracking error (without disturbances)

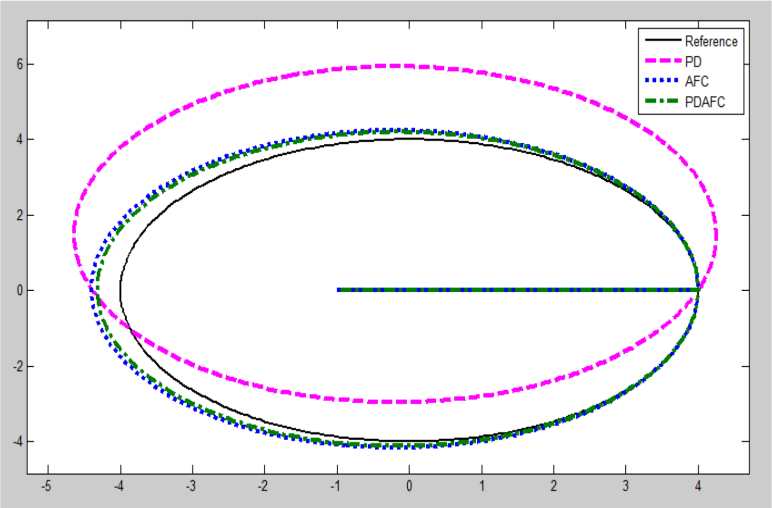


Figure 5.3: Trajectory tracking error (with disturbances)

Figure 5.4 and Figure 5.5 show track errors in x-axis with/without disturbance respectively.

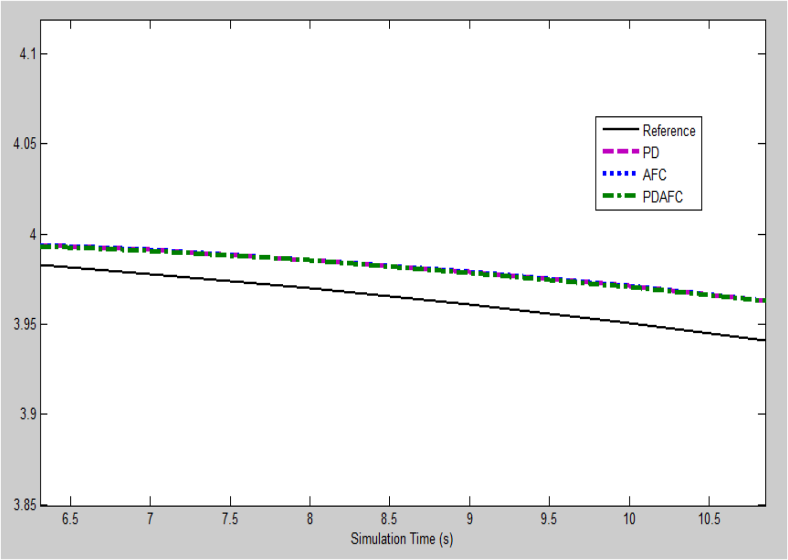


Figure 5.4: Track error x (without disturbances)

Table 5.1 shows the three controllers actual track error x value in comparison with reference value during simulation time 7 to 10s without disturbances.

Table 5.1: Tracking Error x with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
7	3.978088	3.991079	3.991083	3.990656
8	3.970185	3.985687	3.985695	3.985318
9	3.961072	3.97902	3.979032	3.978718
10	3.950753	3.971079	3.971096	3.970857
Average	3.965024	3.981716	3.981726	3.981387

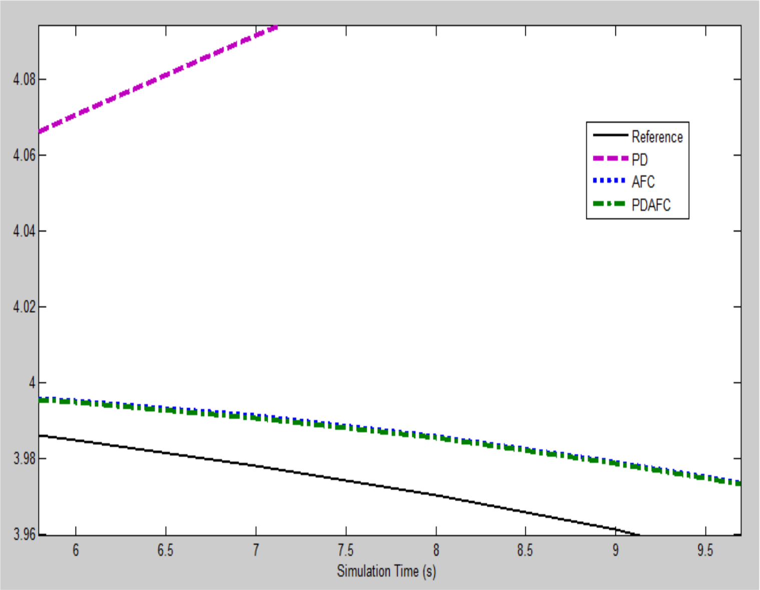


Figure 5.5: Track error x (with disturbances)

Table 5.2 shows the three controllers actual track error x value in comparison with reference value during simulation time 6 to 9s with disturbances.

Table 5.2: Tracking Error x with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
6	3.984779	4.070856	3.995194	3.994762
7	3.978088	4.091906	3.991083	3.990656
8	3.970185	4.111682	3.985695	3.985318
9	3.961072	4.130146	3.979032	3.978718
Average	3.973531	4.101148	3.987751	3.987363

Figure 5.6 and Figure 5.7 show track errors in y-axis with/without disturbance respectively.

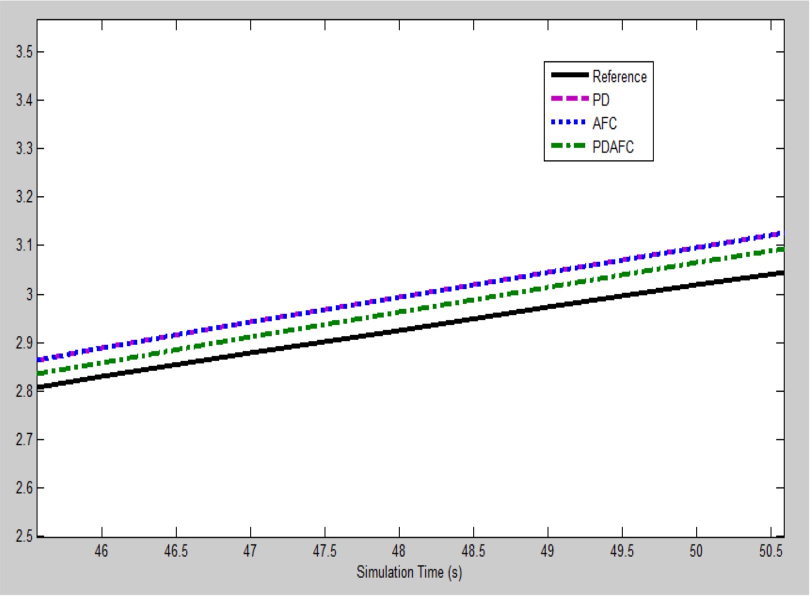


Figure 5.6: Track error y (without disturbances)

Table 5.3 shows the three controllers actual track error y value in comparison with reference value during simulation time 46 to 50s without disturbances.

Table 5.3: Tracking Error y with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
46	2.828427	2.887889	2.858794	2.858794
47	2.877359	2.94132	2.911683	2.911683
48	2.925415	2.993867	2.963696	2.963696
49	2.972579	3.045514	3.014818	3.014818
50	3.018838	3.096245	3.065033	3.065033
Average	2.924524	2.992967	2.962805	2.962805

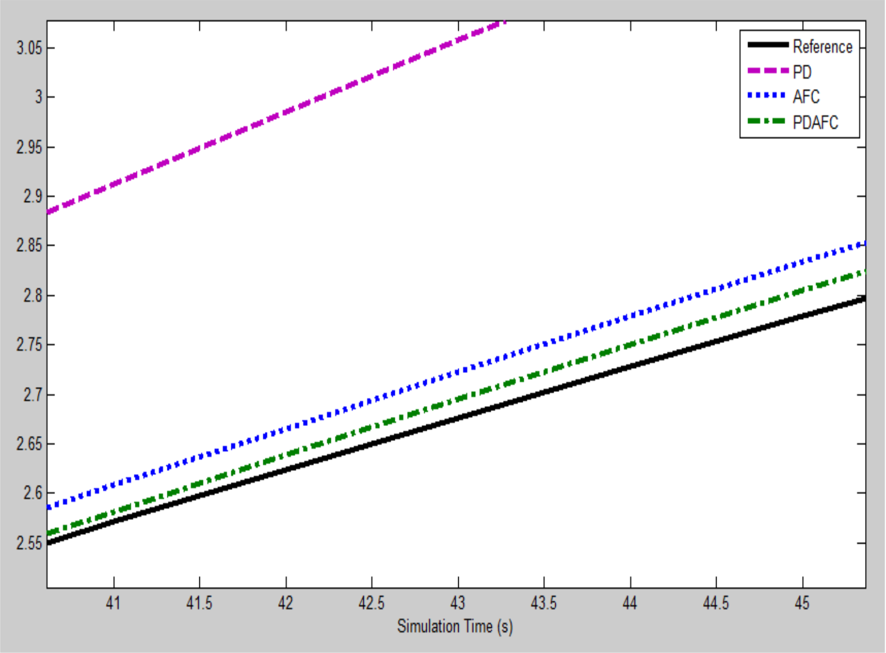


Figure 5.7: Track error y (with disturbances)

Table 5.4 shows the three controllers actual track error y value in comparison with reference value during simulation time 41 to 45s with disturbances.

Table 5.4: Tracking Error y with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
41	2.57115	2.912138	2.608047	2.581793
42	2.624236	2.985388	2.66565	2.638812
43	2.676522	3.058181	2.722453	2.695038
44	2.727993	3.130495	2.778438	2.750455
45	2.778633	3.202307	2.833589	2.805046
Average	2.675707	3.057702	2.721635	2.694229

From Table 5.1, 5.2, 5.3, 5.4, we can conclude that the average tracking error for overall is illustrated in Table 5.5.

Table 5.5: Average Tracking Error of Circle

Control Scheme		PD	AFC	PD+AFC
Without Disturbances	X (error) (%)	0.42098	0.42123	0.41268
	Y (error) (%)	2.34	1.3089	1.3089
	Average (%)	1.38049	0.865065	0.86079
With Disturbances	X (error) (%)	3.2116	0.364	0.348
	Y (error) (%)	14.276	1.7164	0.6922
	Average (%)	8.7438	1.0402	0.5201

5.3 Tracking Errors of Leaf

Figure 5.9 until Figure 5.14 describes the comparison between three different control methods which are PD, AFC and PDAFC controllers in terms of stabilization of the wheel mobile robot. Figure 5.9 and Figure 5.10 show the comparison in trajectory tracking errors. Figure 5.11 and Figure 5.12 show track errors in x-axis. Figure 5.13 and Figure 5.14 show track errors in y-axis. There were almost similar diagram because trajectory tracking errors are very small among three controllers since all the controller are steady in motion control in the case of no disturbances condition which is described at Figure 5.9, Figure 5.11 and Figure 5.13. From Figure 5.10, Figure 5.12 and Figure 5.14, it can be observed and concluded that PD controller has big different value comparing with reference or let say it is unstable during wheel mobile robot motion control when applying disturbances. PD controller is become ineffective when disturbances are applying to the controller. AFC controller is unchangeable which means no big different with reference values, tracking errors in AFC are very small and overlapped the reference diagram. When the disturbances apply on AFC controller, it is still similar to steady state condition because it can effectively eliminate disturbances. Figure 5.8 below shows reference and actual ideal for Leaf.

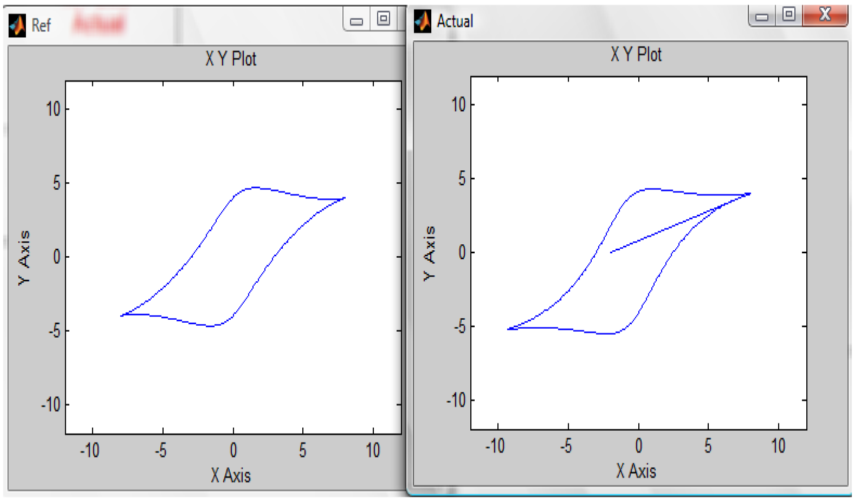


Figure 5.8: Reference and Actual Ideal Diagram

Figure 5.9 and Figure 5.10 show the comparison in trajectory tracking errors.

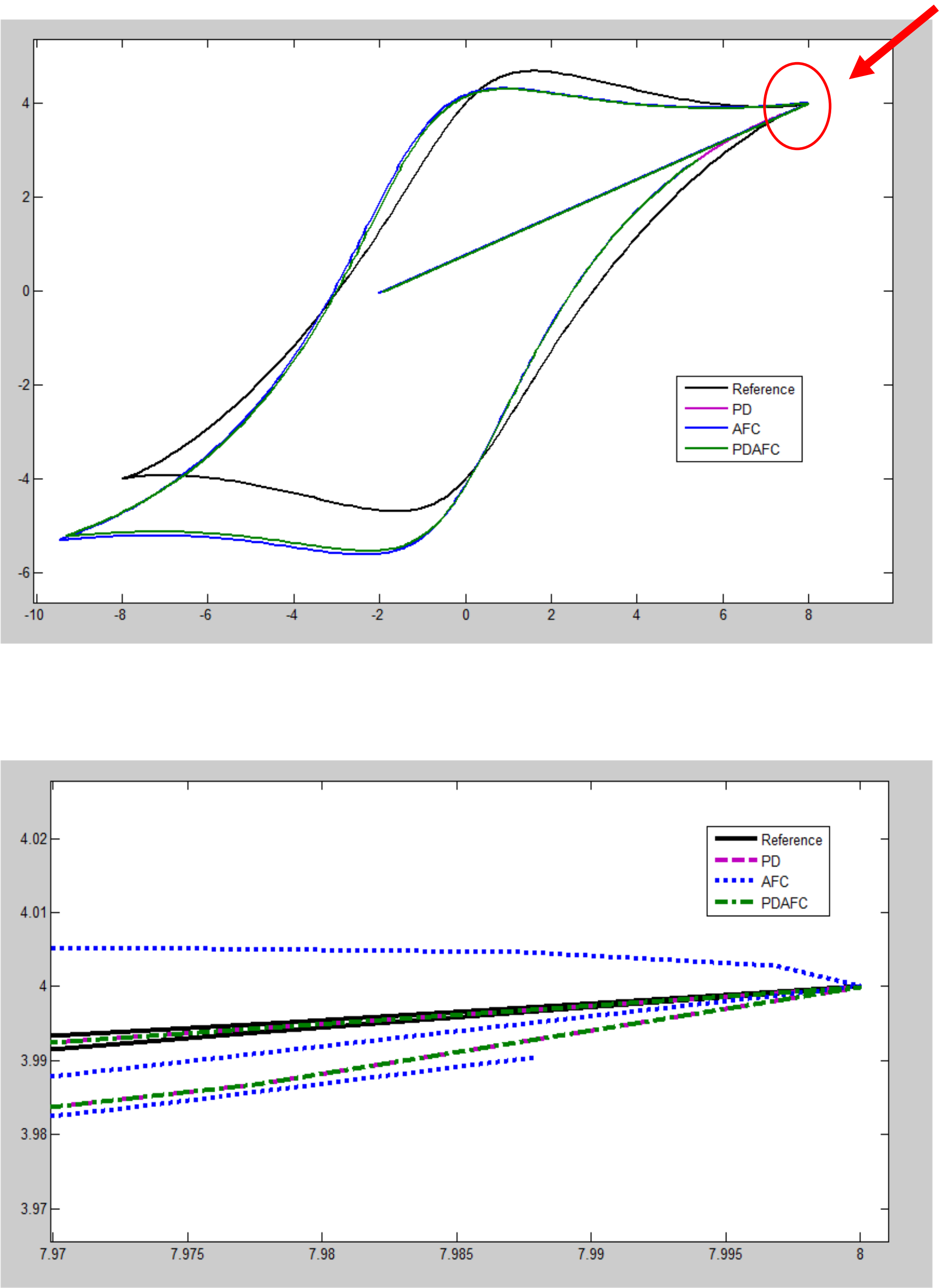


Figure 5.9: Trajectory tracking error (without disturbances)

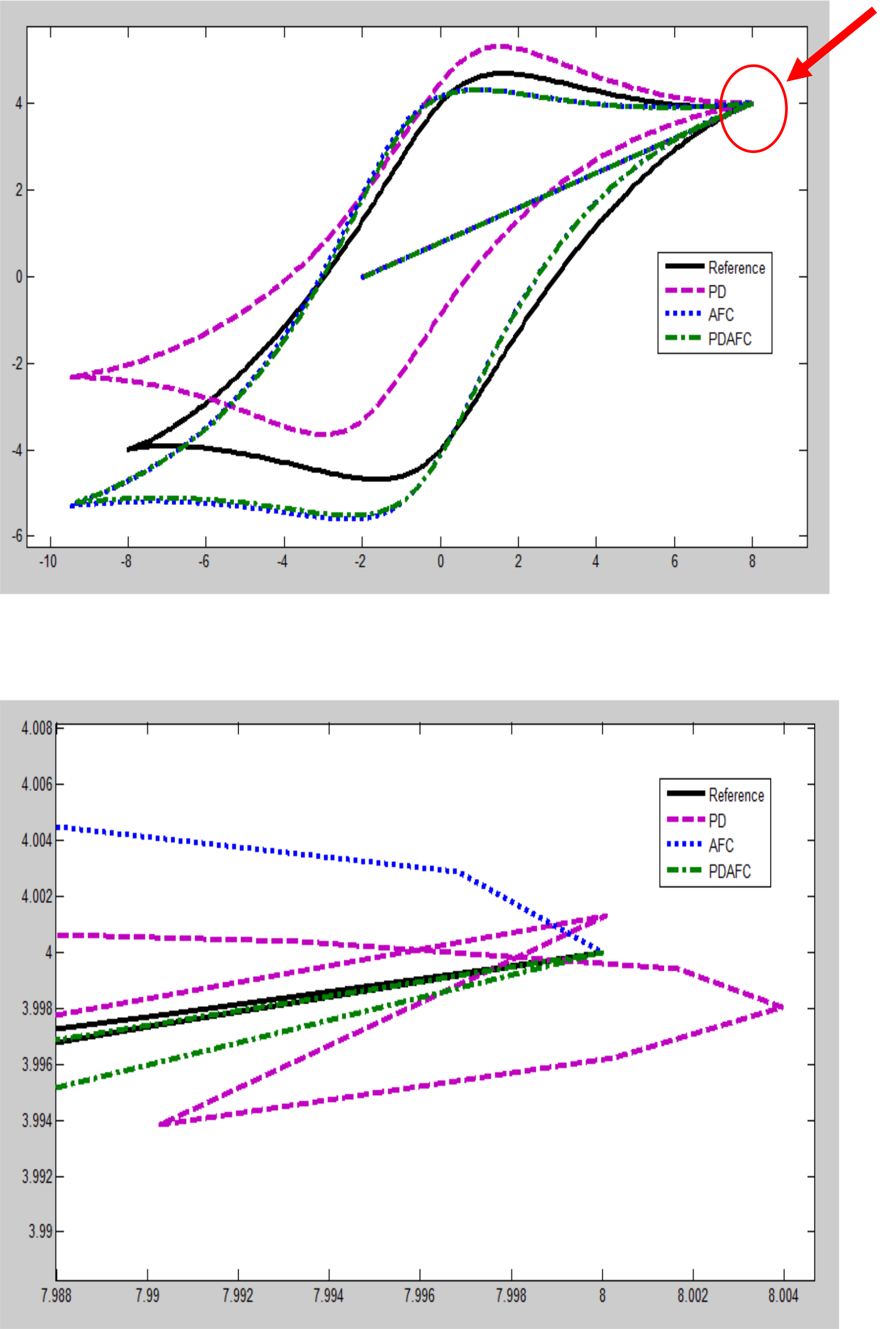


Figure 5.10: Trajectory tracking error (with disturbances)

Figure 5.11 and Figure 5.12 show track errors in x-axis with/without disturbance respectively.

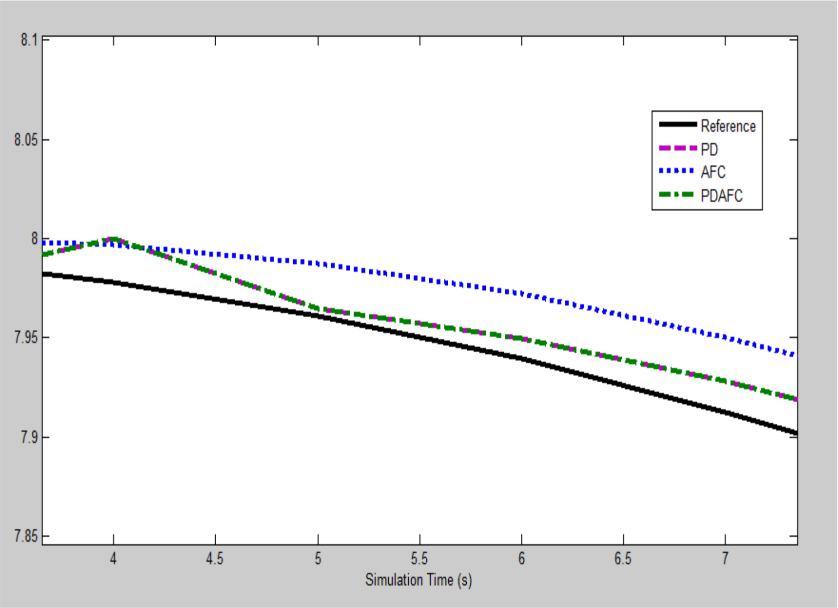


Figure 5.11: Track error x (without disturbances)

Table 5.6 shows the three controllers actual track error x value in comparison with reference value during simulation time 4 to 7s without disturbances.

Table 5.6: Tracking Error x with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
4	7.97809	8.00000	7.99682	8.00000
5	7.96109	7.96498	7.98749	7.96498
6	7.93928	7.94977	7.97201	7.94977
7	7.91270	7.92831	7.95042	7.92831
Average	7.94779	7.96076	7.97669	7.96076

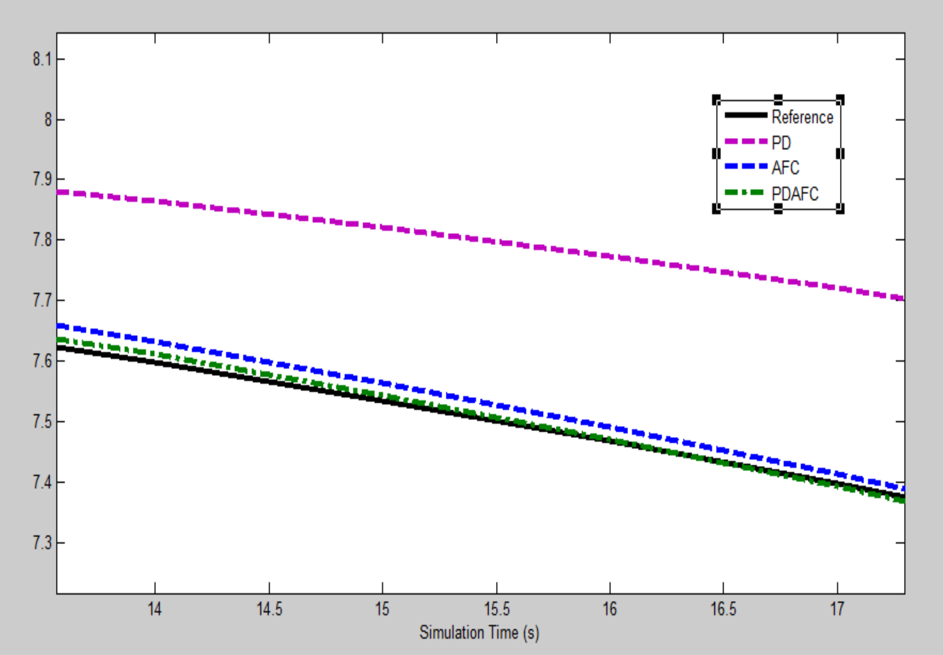


Figure 5.12: Track error x (with disturbances)

Table 5.7 shows the three controllers actual track error x value in comparison with reference value during simulation time 14 to 17s with disturbances.

Table 5.7: Tracking Error x with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
14	7.59773	7.86424	7.63312	7.61109
15	7.53521	7.82158	7.56519	7.54383
16	7.46858	7.77360	7.49198	7.47135
17	7.39796	7.72044	7.41364	7.39380
Average	7.49987	7.79497	7.52598	7.50502

Figure 5.13 and Figure 5.14 show track errors in y-axis with/without disturbance respectively.

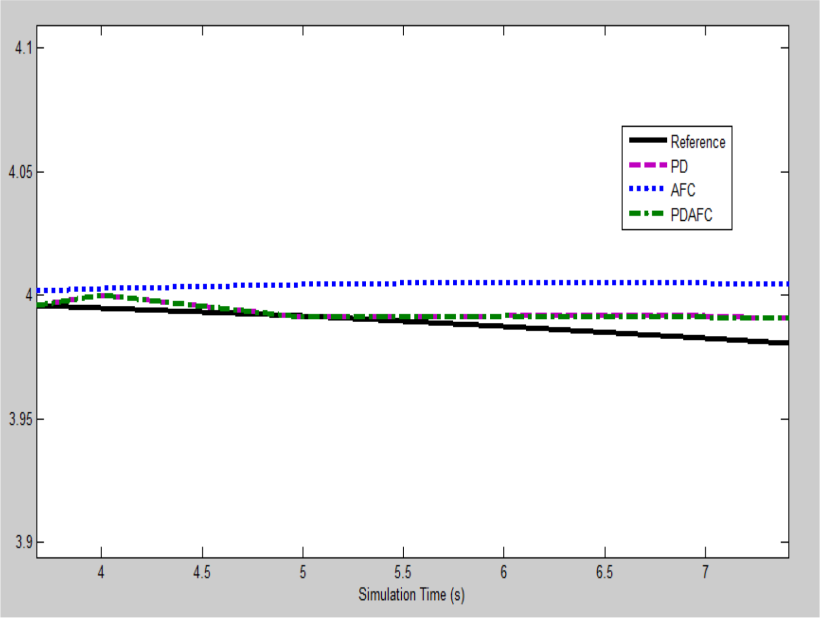


Figure 5.13: Track error y (without disturbances)

Table 5.8 shows the three controllers actual track error y value in comparison with reference value during simulation time 4 to 7s without disturbances.

Table 5.8: Tracking Error y with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
4	3.995	3.999	4.002	3.999
5	3.991	3.991	4.004	3.991
6	3.987	3.991	4.005	3.991
7	3.982	3.991	4.004	3.991
Average	3.989	3.993	4.004	3.993

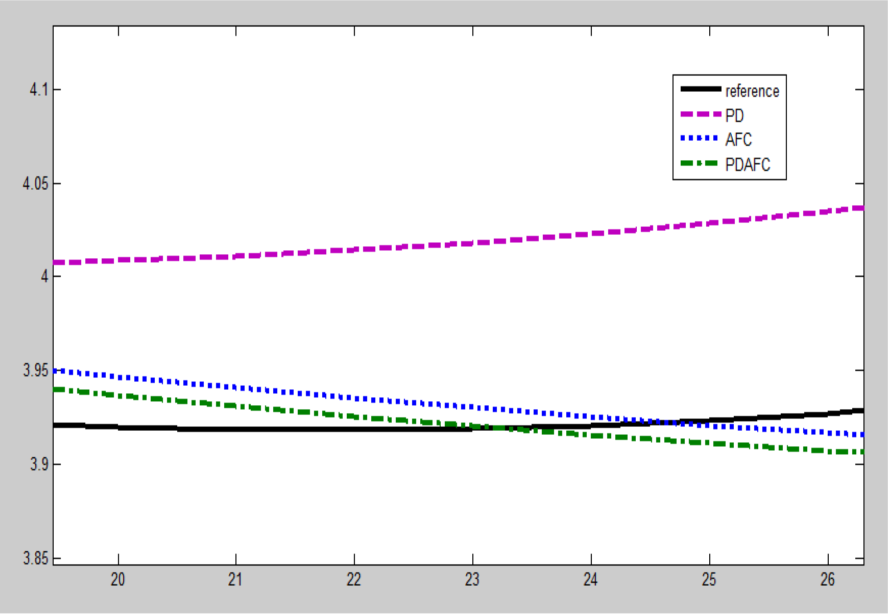


Figure 5.14: Track error y (with disturbances)

Table 5.9 shows the three controllers actual track error y value in comparison with reference value during simulation time 21 to 24s with disturbances.

Table 5.9: Tracking Error y with Simulation Time

Simulation Time (s)	Reference	PD	AFC	PD+AFC
21	3.91880	4.01106	3.94089	3.93113
22	3.91841	4.01423	3.93538	3.92567
23	3.91900	4.01810	3.93015	3.92050
24	3.92063	4.02274	3.92527	3.91567
Average	3.91921	4.01653	3.93292	3.92324

From Table 5.6, 5.7, 5.8, 5.9, we can conclude that the average tracking error for overall is illustrated in Table 5.10.

Table 5.10: Average Tracking Error x with Simulation Time

Control Scheme		PD	AFC	PD+AFC
Without Disturbances	X (error) (%)	0.163	0.364	0.163
	Y (error) (%)	0.1108	0.3807	0.1107
	Average (%)	0.1369	0.37235	0.13685
With Disturbances	X (error) (%)	3.935	0.348	0.067
	Y (error) (%)	2.483	0.3498	0.1028
	Average (%)	3.209	0.3489	0.0849

5.4 Discussion

From the table 5.2, the tracking error values are taken by comparing reference value and actual value among three different controllers. Without disturbances condition for Circle, both three controllers show similar results or almost same value of average tracking error which are 1.38049%, 0.865065% and 0.86079%. However, the values of average tracking errors have big difference among three controller with disturbances condition with values equal to 8.7438%, 1.0402%, 0.5201%.

Besides that, the tracking errors of Leaf has been done as illustrated in Table 5.10. Without disturbances condition, both three controllers shows similar results or almost same value of average tracking errors which was 0.1369% for PD controller, 0.37335% for AFC controller, and 0.13685% for PD+AFC controller. However, the value of average tracking error were big different among three controller at with disturbances condition which was 3.209%, 0.3489% and 0.0849%.

PD controller cannot avoid disturbance and the tracking errors parameters have the following values:- 8.7438% and 3.209% with applying disturbances. However AFC controller and PDAFC controller can effectively eliminate the presence of disturbance. AFC controller remains unchanged and robust during wheel mobile robot motion although disturbances are applied to it. The tracking errors have value equal to 0.37335% at without disturbances condition and 0.3489% with disturbances condition.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In conclusion, there were no big differences between reference and actual path for all controllers PD, AFC and PD-AFC without disturbance condition. From simulation results, PD, AFC and PDAFC controller diagram are overlapped each other due of too small tracking error without disturbances condition. But, traditional controller PD shows big difference in average tracking errors (ATE) comparing to AFC and PDAFC controllers with applying disturbances condition. The results show that traditional controller, PD controller cannot afford uncertainties and become unstable after applying disturbances. However, AFC controller is effectively eliminate disturbances and become stable during wheel mobile robot motion. In a nutshell, the wheel mobile robot motion control remains stable and robust even in presence of disturbance by using AFC method.

6.2 Recommendations for Future Research

This study provides an overview of Active Force Controller in eliminate disturbances. However, there are some factors which need to be improved to obtain more accurate results. The following are some recommendations for future research purpose:

(a) Find another way for solving non-square matrix problem in MATLAB/ simulink.
(b) Extend to another type of disturbances and operating conditions.
(c) Additional trajectories can be investigated such as triangle, square, etc with AFC.

REFERENCES

This thesis is prepared based on the following references;

Abdullah, S., Mailah, M., & Hing, C. T. H. (2013). Feedforward Model Based Active Force Control of Mobile Manipulator using MATLAB and MD Adams.*WSEAS Transactions on Systems*, *12*, 314-324.

Hashemi-Dehkordi, S. M., Abu-Bakar, A. R., & Mailah, M. (2012). Reducing friction-induced vibration using intelligent active force control (AFC) with piezoelectric actuators. *Sadhana*, *37*(6), 637-655.

Hewit, J. R., & Burdess, J. S. (1981). Fast dynamic decoupled control for robotics, using active force control. *Mechanism and Machine Theory*, *16*(5), 535-542

Jahanabadi, Hossein (2010) Intelligent active force control of a human-like arm actuated by pneumatic artificial muscles.

Jahanabadi, H., Mailah, M., Zain, M. M., & Hooi, H. M. (2011). Active force with fuzzy logic control of a two-link arm driven by pneumatic artificial muscles. *Journal of Bionic Engineering*, *8*(4), 474-484.

Kozłowski, K., & Pazderski, D. (2004). Modeling and control of a 4-wheel skid-steering mobile robot. *Int. J. Appl. Math. Comput. Sci*, *14*(4), 477-496.

Kwek, L. C., Kang, C. C., Loo, C. K., & Wong, E. K. (2005). Implementation of evolutionary active force control in a 5-link biped robot. *Intelligent Automation & Soft Computing*, *11*(3), 167-178.

Kwek, L. C., Wong, E. K., Loo, C. K., & Rao, M. V. C. (2003). Application of active force control and iterative learning in a 5-link biped robot. *Journal of Intelligent and Robotic Systems*, *37*(2), 143-162.

Mailah, M., Abdullah, S., & Hing, T. H. (2013). Tracking Performance on Feedfoward Model Base Active Force Control of Mobile Manipulator using Matlab and Adams. *Recent Advances in Electrical Engineering Series*, (11).

Mailah, M., Pitowarno, E., & Jamaluddin, H. (2006). Robust motion control for mobile manipulator using resolved acceleration and proportional-integral active force control. *arXiv preprint cs/0601057*.

Mohammed A. H. Ali, Musa Mailah, Hamedon, B., & Yussof, Z. B.(2015). Wheeled Mobile Robot Path Control in a Complex Trajectory using HybridMethods.

Onn, N., Hussein, M., TANG, C. H. H., Zain, M. Z. M., Mohamad, M., & Ying, L. (2013). Active Force Control with Nonlinear Predictive Control based on Receding-Horizon Cost Function Optimization for Five-Link Biped Model in Sagittal Plane.

Tang, H. H., Mailah, M., & Jalil, M. K. A. (2012). Robust intelligent active force control of nonholonomic wheeled mobile robot. *Jurnal Teknologi*, *44*(1), 49-64.

Appendices A1

	2015				2016					
Activities	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**
Literature Review	🟦	🟦								
Proposal Preparation		🟦	🟦							
Modelling and Design				🟦	🟦					
Simulation of Wheel Mobile Robot					🟦	🟦	🟦			
Evaluation of Controller							🟦	🟦	🟦	
Thesis Writing									🟦	🟦