DESIGN OF FUZZY LOGIC CONTROLLER FOR TWO WHEEL MOBILE ROBOT

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DECLARATION

I BASHIR MUHAMMAD DAHIRU hereby declare that this work is the product of my research efforts undertaken under the supervision of Dr. Nura Magaji and has not been presented anywhere for the award of a degree or certificate. All sources have been duly acknowledged.

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CERTIFICATION

This is to certify that the research work for this dissertation and the subsequent write-up by BASHIR MUHAMMAD DAHIRU (SPS/12/MEE/00022) were carried out under my supervision

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ABSTRACT

Automation is the order of the day in our daily activities, since most of business places utilize robot for high efficiency and productivity. Most robot system is highly complex and nonlinear therefore, its dynamic and kinematic equations are also highly nonlinear and difficult to realize. In that context their approximate dynamic or kinematic model are mostly available. This dissertation proposes an intelligent Fuzzy Logic Controller (FLC) for the control of a two wheel mobile robot system, the input to the controller are angle error and its derivative which are manipulated using fuzzy rule base to produce a control signal that controls the movement of the robot, this is achieved using Fuzzy Inference System (FIS) in Matlab/Simulink environment. On the other hand, Proportional-Integral-Differential (PID) controller was also designed for the same system using Matlab/Simulink, for the purpose of comparison. The results obtained from the responses of the controllers show that FLC demonstrated superiority to PID controller in some of performance indices used. For example response for fuzzy logic controller under a unit step input has 0.89sec settling time and 0.44seconds rise time respectively while PID controller produced a settling time of 1.68sec, and 0.88seconds rise time respectively, this shows a superiority of FLC, also in terms of robot position along y-axis, the response of FLC has a settling time of 8.53seconds and 1.2seconds rise time respectively, as against PID controller which produced a settling time of 9.71seconds and 8.06seconds rise time respectively. Comparing these results obtained both from robot linear velocity and position of the robot in terms of x and y axes respectively, with the results of the control signal obtained based on their magnitude, the proposed fuzzy logic controller could be a valuable and efficient controller for the robot system.

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CHAPTER ONE

Introduction

1.1 Background

Mobile robots are mechanical devices capable of moving in an environment with a certain degree of autonomy. Autonomous navigation is associated to the availability of external sensors that capture information of the environment through visual images or distance or proximity measurements. The most common sensors are distance sensors (ultrasonic, laser, etc) capable of detecting obstacles and of measuring the distance to walls close to the robot path. When advanced autonomous robots navigate within indoor environments (industrial or civil buildings), they have to be endowed with the ability to move through corridors, to follow walls, to turn corners and to enter open areas of the rooms.

In attempts to formulate approaches that can handle real world uncertainty, researches are frequently faced with the necessity of considering tradeoffs between developing complex cognitive systems that are difficult to control, and adopting a host of assumptions that lead to simplified models which are not sufficiently representative of the system or the real world. The latter option is a popular one which often enables the formulation of viable control laws. However, these control laws are typically valid only for systems that comply with imposed assumptions, and furthermore, only in neighbourhoods of some nominal state. The option that involves complex systems has been less prevalent due to that lack of analytical methods that can adequately handle uncertainty and concisely represent knowledge in practical control systems.

The two wheels mobile robot system takes output angular position of a Permanent Magnet DC motor as an actuator input, and outputs the rotational speed of the two wheels, the actuator most used for mobile robot is PMDC motor, because their torque-speed characteristics are achievable with different electrical configurations and their speeds can be smoothly controlled and in most cases are reversible. DC Motor control system design and its features can be analyzed by MATLAB software. One application form of mobile robot is line follower wheelchair, to help and support people with disabilities and special needs to perform specific predetermined tasks e.g. religious rituals.

Autonomous mobile robots have various applications in the field of industry, military and security environment. The problem of autonomous motion planning and control of wheeled mobile robots have attracted lot of research interest in the field of robotics. Consequently engineers working on design of mobile robots have proposed various drive mechanisms to drive such robots. However the most common way to build a mobile robot is to use two-wheel drive with differential steering and a free balancing wheel (castor). Controlling the two motors independently make such robots to have good manoeuvring and work well in indoor environment. Mobile robots with such drive systems are typical example of non-holonomic mechanisms due to the perfect rolling constraints on a wheel motion (no longitudinal or lateral slipping) [9].

Since time immemorial there has been a constant effort to build and construct a conscious machine (robot) that should be capable of thinking like human beings, for this there is a tremendous craze among the modern thinkers, philosophers and researchers. Here, this work is mainly focusing on robotics and its potential utility in engineering, medical, industries, mines biomedical science and many more. So what is there in robotics that has attracted thousands of scholars from various backgrounds and most probably each of them having different requirement. This is because robots can work as conscious as that of a human being. Robots need very less human involvements; this is another big advantage of adopting robotics in real life. Now, moving towards autonomous mobile robot, i.e., it should be capable of doing things in an undefined and unmodified environment and without human interventions. In simple words it should be capable of acting in a real world environment. A well to do autonomous robot should be capable of doing many things like,

i. With no difficulty it should be able to collect information about the surrounding.
ii. It must travel from one destination to another with no human assistance.
iii. Must avoid obstacle in its path.
iv. If necessary act according to the situations.

Now the prime focus is how to develop techniques for autonomous mobile robot navigation. Developing navigational techniques has attracted many researchers, students and become one of the major trends in navigational robotics. This trend is highly motivated by the current thin gap between the available technology and the new user application demand. One of the major problems in industrial robotics is that lack of flexibility, autonomy, frequent breakdown: usually, these robots only perform pre-programmed or pre-defined sequences of operations in highly constrained environments, and are not able to operate in partially new or completely environments or to face unexpected situations. In these conditions they are no better than dead matter. Now in the current market scenario there is a heavy competition for complete autonomous robots. There are so many soft computing techniques used for mobile robot navigation such as neural network and genetic algorithm, particle swarm optimization and are also considered to be the best way for expressing the subjective uncertainties in human mind. If navigation is of so much interest then what is navigation? How it works? To answer these questions there is need to think very carefully; navigation is the process of determining and maintaining a specific path that is free of obstacles and optimized one and leads to the final destination. Fuzzy logic control system provides a wonderful platform in which human perception-based action can be easily performed. Using the fuzzy logic control system, the way human being thinks and makes decision can be formulated and implemented in robotics by simple IF–THEN rules and can be combined with easily understandable and natural linguistic representations. Localization map and cognition path planning are the two most vital sub systems for the fuzzy interface technique. These two subsystems are incorporated and utilized in the fuzzy logic control system as fuzzy rule sets. The input to the fuzzy system is the perception information by the sensors about the environment and the output is in terms of motion control of the robot: slow, fast, left turn, right turn, straight motion and heading angle.

1.2 Scope and Limitation

This research is concerned with the development of fuzzy logic for the control of two wheel mobile robot. However, it has the following limitations:

(i) the Fuzzy logic controller was based on simulation but not practical implementation

(ii) That only two possible movement direction were considered for this research**.**

1.3 Aim and Objectives

The main aim of this dissertation is to design a fuzzy logic controller for the control of two wheels mobile robot system.

In order to archive the aim, the following objectives are drawn:

i. to adopt and improve a kinematic model of two wheel mobile robot;

ii. To design a fuzzy logic controller for two wheel mobile robot;

iii. To test the performance of the proposed fuzzy logic controller against conventional controller (PID).

1.4 Methodology

In order to develop a model of two wheel robot, first the model of a Permanent magnet DC motor (PMDC) used as an actuator being attached to each wheel of the robot will be developed in terms of dynamic equations. The robot is considered to be on the Cartesian plane moving in a straight line with linear velocity leaving a base frame describes as $q = [x\ y\ \theta]$ to a moving frame $q = \left[x\ y\ \theta\right]$ and followed a curved trajectory with an angular velocity. To obtain the kinematic equations, the moving linear velocity of the robot will be resolve into x and y components to get Vx and Vy respectively.

The fuzzy logic controller will be developed using Mamdani fuzzy inference system (FIS) because it is intuitive, widespread acceptance and well suited for human input and was among the first control system built using fuzzy set theory. The controller has two inputs and one output, the inputs to the controller are angle error and its derivative. This can be achieved using Fuzzy Inference System (FIS) in the Matlab/Simulink environment. Each input has five membership functions (MF) while the output with seven membership functions (MF), combining these inputs membership functions will produce twenty five rule bases which will serve as control signals of the controller. Having these at hand, the fuzzy logic controller can easily be design using lookup table in the Matlab/Simulink environment.

The performance of the whole system in terms of robot linear velocities and positions along x and y directions can be archived and tested base on the proposed fuzzy logic controller alongside PID controller using the performance index like settling time; rise time and percentage overshoot deduced from the simulation in the Matlab/Simulink environment.

1.5 Report Organisation

The main objective of this dissertation is to develop a control system base on fuzzy for the control of two wheel mobile robot system. The rest of the report are organise as follows chapter one covering the introduction, scope and limitation and methodology, chapter two covering the review of related literature and theoretical background of the controller used. Mathematical modelling and controller design are presented in chapter 3, and chapter 4 consider the presentation and discussion of result, finally, chapter five conclude and provide recommendations for further studies.

CHAPTER TWO

Literature Review

2.1 Introduction

In this chapter the details literature review of fuzzy logic and PID alongside their basics are discussed. Differential drive, inverse kinematic and different type of robot are also discussed, finally, the concept of two wheel mobile robot and robotic wheel are discussed.

2.2 Fuzzy Logic Controller Basics

The human brain interprets imprecise and incomplete sensory information provided by perceptive organs. Fuzzy set theory provides a systematic calculus to deal with such information linguistically, and it performs numerical computation by using linguistic labels stipulated by membership functions. A fuzzy inference system (FIS) when selected properly can effectively model human expertise in a specific application. In this chapter the basic terminology of fuzzy logic is discussed, giving a detailed explanation of all the aspects involved. Later the design of the fuzzy logic controller used in this thesis is given. A classic set is a crisp set with a crisp boundary. For example, a classical set A of real numbers greater than 6 can be expressed as

$$A = \{x/x > 10\} \tag{2.1}$$

Where there is a clear, unambiguous boundary 10 such that if x is greater than this number, then x belongs to this set A; or otherwise does not belong to this set. Although classical sets are suitable for various applications they do not reflect the mature of human concepts and thoughts, which tend to be abstract and imprecise. In contrast to a classical set, a fuzzy set, as the name implies, is a set without a crisp boundary. That is, the transition from "belongs to a set” to “does not belong to a set” is gradual, and this smooth transition is characterized by membership functions that give fuzzy sets flexibility in modelling commonly used linguistic expressions, such as “the water is hot” or “the temperature is high”. The fuzziness does not come from the randomness of the constituent members of the set, but from the uncertainties and imprecise nature of abstract thoughts and concepts.

2.2.1 Basic Definitions and Terminology

By defining a characteristic function for each element x in X, one can represent a classical set A by a set of ordered pairs (x, 0) or (x, 1), which indicates $x\ not\ belongs\ to\ A\ or\ x\ is\ belongs\ to\ A\ respestively.$

Unlike the classical set, a fuzzy set expresses the degree to which an element belongs to a set. Hence the characteristic function of a fuzzy set is allowed to have values between 0 and 1, which denotes the degree of membership of an element in a given set.

If X is a collection of objects denoted generically by x, then a fuzzy set A in x is defined as a set of ordered pairs:

$$A = \{(x, \mu_A(x)|x \in X\} \tag{2.2}$$

Where $\mu_A(x)$ is called the membership function (MF) for the fuzzy set A. The MF maps each element of x to a membership value between 0 and 1. It is obvious that if the value of the membership function $\mu_A(x)$ is restricted to either 0 or 1, then A is reduced to a classical set and $\mu_A(x)$ is the characteristic function of A. Usually X is referred to as the universe of discourse, or simply the universe, and it may consist of discrete (ordered or unordered) objects or continuous space.

The construction of a fuzzy set depends on two things: the identification of a suitable universe of discourse and the specification of an appropriate membership function. Therefore, the subjectivity and non-randomness of fuzzy sets is the primary difference between the study of fuzzy sets and probability theory.

In practice, when the universe of discourse X is a continuous space, one can usually partition X into several fuzzy sets whose MFs cover x in a more or less uniform manner. These fuzzy sets, which usually carry names that are appearing in our daily linguistic usage, such as "large," "medium," or "negative" are called linguistic values or Linguistic labels.

2.2.2 Membership Functions (MF)

As discussed above a fuzzy set is completely parameterized by its MF. Since most fuzzy sets have a universe of discourse X consisting of the real line R, it would be impractical to list all the pairs defining a membership function. So a MF is expressed with the help of a mathematical formula. A MF can be parameterized according to the complexity required. These also could be one dimensional or multi dimensional. Here are a few classes of parameterized MFs of one dimension that is MFs with a single input.

A triangular MF is specified by three parameters {a, b, c} as follows

$$triangle(x; a, b, c) = \begin{matrix} 0, & x < a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \\ 0 & c \leq x \end{matrix} \quad (2.3)$$

By using min and max, one have an alternative expression for the preceding equation

$$triangle(x; a, b, c) = max\left(min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \quad (2.4)$$

The parameters {a, b, c} (with a<b<c) determine the x coordinates of the three corners of the underlying triangular MF.

A trapezoidal MF is specified by four parameters {a, b, c, d} as follows

$$trapezoid(x; a, b, c, d) = \begin{cases} 0, & x < a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \\ 0, & d \leq x \end{cases} \tag{2.5}$$

An alternative concise expression using min and max is

$$trapezoid(x; a, b, c, d) = \max\left(\min\left(\frac{\mathrm{x-a}}{\mathrm{b-a}}, 1, \frac{\mathrm{d-x}}{\mathrm{d-c}}\right), 0\right) \tag{2.6}$$

The parameter {a, b, c, d} (with a < b < c < d) determine the x coordinates of the four corners of the underlying trapezoidal MF.

A Gaussian MF is specified by two parameters {c , σ}

$$gaussian = (x; c, \sigma) = e^{-\frac{1}{2}\left(\frac{x-c}{\sigma}\right)2} \tag{2.7}$$

A Gaussian MF is determined completely by c and σ ; c represents the MFs centre and σ determines the MFs width.

A generalized bell MF (or bell MF) is specified by three parameters {a, b, c}

$$bell(x; a, b, c) = \frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \tag{2.8}$$

Where the parameter b is usually positive. It is also called as the Cauchy MF.

A sigmoidal MF is defined by

$$sig(x; a, c) = \frac{1}{1+\exp\left[-a(x-c)\right]} \tag{2.9}$$

Where a controls the slope at the crossover point x=c. Sigmoidal functions are widely used as the activation function of artificial neural networks.

2.2.3 Linguistic Variables and Fuzzy If-Then Rules

The concept of linguistic or "fuzzy" variables was presented in [43]. Think of them as linguistic objects or words, rather than numbers. The sensor input is a noun, e.g. "temperature," "displacement," "velocity," "flow," "pressure," etc. Since error is just the difference, it can be thought of the same way. The fuzzy variables themselves are adjectives that modify the variable (e.g. "large positive" error, "small positive" error, "zero" error, "small negative" error, and "large negative" error). As a minimum, one could simply have "positive", "zero", and "negative" variables for each of the parameters.

Additional ranges such as "very large" and "very small" could also be added to extend the responsiveness to exceptional or very nonlinear conditions, but aren't necessary in a basic system. Once the linguistic variables and values are defined, the rules of the fuzzy inference system can be formulated. These rules map the fuzzy inputs to fuzzy outputs.

$$if\ x\ is\ A\ t\ \ en\ y\ is\ B \qquad (2.10)$$

Where A and B are linguistic values defined by fuzzy sets on universe of discourse X and Y, respectively. “x is A “ is called the antecedent or premise, while “y is B” is called the consequent or conclusion. This rule is also abbreviated as A →B.

The antecedent normally consists of some combination of the inputs and the consequent consists of output variables.

2.2.4 Fuzzy Inference Systems

There are three main fuzzy logic inference systems (fuzzy logic approximations):

Mamdani type, Sugeno type, and Tsukamoto type, of these Mamdani fuzzy inference system is used. The Mamdani type of fuzzy logic controller contains four main parts, two of which perform transformations.

The four parts are

• Fuzzifier (transformation 1);

• Knowledge base;

• Inference engine (fuzzy reasoning, decision-making logic);

• Defuzzifier (transformation 2).

The fuzzifier performs measurements of the input variables (input signals, real variables), scale mapping and fuzzification (transformation 1). Thus all the monitored signals are scaled, and fuzzification means that the measured signals (crisp input quantities which have numerical values) are transformed into fuzzy quantities (which are also referred to as linguistic variables in the literature). This transformation is performed using membership functions. In a conventional fuzzy logic controller, the number of membership functions and the shapes of these are initially determined by the user. A membership function has a value between 0 and 1, and it indicates the degree of belongingness of a quantity to a fuzzy set. If it is absolutely certain that the quantity belongs to the fuzzy set, then its value is 1, but if it is absolutely certain that it does not belong to this set then its value is 0.

The membership functions can take many forms including triangular, Gaussian,bell shaped, trapezoidal, etc. The knowledge base consists of the data base and the linguistic control rule base. The data base provides the information which is used to define the linguistic control rules and the fuzzy data manipulation in the fuzzy logic controller. The rule base defines (expert rules) specifies the control goal actions by means of a set of linguistic rules. In other words, the rule base contains rules such as would be provided by an expert. The FLC looks at the input signals and by using the expert rules determines the appropriate output signals (control actions). The rule base contains a set of if–then rules. The main methods of developing the rule base are:

• Using the experience and knowledge of an expert for the application and the control goals;

The inference engine (reasoning mechanism) is the kernel of FLC and has the capability both of simulating human decision making based on fuzzy concepts and inferring fuzzy control actions by using fuzzy implications and fuzzy logic rules of inference. In other words, once all the monitored input variables are transformed into their respective linguistic variables (by transformation 1), the inference engine evaluates the set of if- then rules (given in the rule base) and thus a result is obtained which is again a linguistic value for the linguistic variable. The linguistic result has to be transformed into a crisp output value of the FLC and this is why there is a second transformation in the FLC.

The second transformation is performed by the defuzzifier which performs scale mapping as well as defuzzification. The defuzzifier yields a non fuzzy, crisp control action from the inferred fuzzy control action by using the consequent membership functions of the rules.

2.2.5 Defuzzification

There are many defuzzification techniques some of which are discussed here.

(i)Centroid of Area

$$COA = \frac{\int \mu_A(z) z dz}{\int \mu_A(z) dz} \quad (2.11)$$

Where $\mu_A(z)$ the aggregated output MF and z is the output quantity. This is the most widely adopted defuzzification.

(ii)Mean-Max Method (Middle of Maxima (Mom) Method)

In this defuzzification technique, the average output value

$$z = \frac{z_1 + z_2}{2} \quad (2.12)$$

Is obtained, where z_1 is the first value and z_2 is the last value, where the output overall membership function, $\mu_A(z)$,is maximum.

(iii) First of Maxima (FOM) Method

Using this defuzzification technique, the first value of the overall output membership function with maximum membership $\mu_A(z)$degree is taken. It should be noted that this is equal to z_1 used in the MOM defuzzification method.

(iv)Last of Maxima (Lom) Method

Using this defuzzification technique, the last value of the overall output membership function with maximum membership $\mu_A(z)$ degree is taken. It should be noted that this is equal to z_2 used in the MOM defuzzification method. In general, the defuzzification operations are time consuming and they are not easily subject to rigorous mathematical analysis.

2.3 Fuzzy Logic Controller

According to previous work carried out on fuzzy logic controllers in different fields of application, it shows that fuzzy logic approach has been proved to be a simple and powerful technique for control problems. Applying it through behaviour based modular architecture comes with great simplification in design process but time consuming. Fuzzy control approach has been used by many researchers in sensor based navigation control of mobile robots. According to [1], a comparison between proportional controllers for wall follow robot behaviour was presented. FLC had shown better performance than P controller in early reaching the steady state but the better result could be archived if PID controller was incorporated in the whole system. In that paper, the navigation of Khepra I mobile robot in a simulated dynamic environment has been investigated using fuzzy logic control approach. In another paper presented in [2], it demonstrated behaviour based fuzzy logic controller. The robot in that design was able to reach its goal avoiding obstacles but it might get into trap situation, the span of the control action by fuzzy logic controller could be extended by increasing the number of rule bases so that the robot can reach its goal even in the trap situation.

Similar work was carried out in [3], this paper describes an application of fuzzy logic in designing controllers for industrial plants. According to [3], a fuzzy logic is used to synthesize linguistic control protocol of a skilled operator. The method has been applied to pilot scale plants as well as in a practical industrial situation. In this work, it illustrated the potential for using fuzzy logic in modelling and decision making. But a better performance of the skilled operator could be attained by incorporating PID controller in the system for comparison.

The implementation of fuzzy logic control shows its robustness as the results in case of both simulation and experiment remain identical with respect to the load mass change [5]. Still on this paper, it demonstrated the performance of two types of fuzzy logic-based controllers-sugeno based and mamdani based which shows the main difference between them as the sugeno output membership functions are either linear or constant. Also they differ in the consequents of their fuzzy rules, and thus their aggregation and defuzzification differ suitably [6].

According to [7], the fuzzy temperature controller is designed and implemented in microcontroller without using any special software tool. Unlike some fuzzy controllers with hundreds, or even thousands of rules running on computer systems, a unique FLC using a small number of rules and simple implementation is demonstrated to solve a temperature control problem with unknown dynamics or variable time delays commonly found in industry. In this paper, it minimizes the total cost of hardware and software design. The control result can be improved by resizing the fuzzy sets and finer tuning for the membership functions.

According to paper presented in [8], the experimental results demonstrated that the proposed navigation system is flexible to approach different problems and tasks in a cluster environment where different objects are located to obstruct the robots path to goal. It can be implemented on the physical mobile robot functioning in a real world scenario and allows the mobile robot to safely complete its task within an optimum travel distance and reasonable amount of time without experiencing any collision [8]. Better performance of the controller could be archived by increasing the number of rule bases since the robot is acting in a cluster environment.

In another paper presented in [9], it focuses on Kinematics, Localization and closed loop motion control of a differential drive mobile robot which is capable of navigating to a desired goal location in an obstacle free static indoor environment. Two trajectory planning approaches are made (i) the robot is rotated to eliminate orientation error and then translate to overcome distance error (ii) Both rotational and translational motion is given to the robot to overcome orientation and distance error simultaneously. Localization is estimated by integrating the robot movement in a fixed sampling frequency. The control law is based on kinematics model which provides updated reference speed to the high frequency PID control of DC motor. Stability of proposed control law is validated by Lyapunov Criterion. Both experimental and simulation results confirm the effectiveness of the achieved control algorithms and their efficient implementation on a two wheeled differential drive mobile robot using an 8-bit microcontroller [9]

Similarly in a paper presented in [11], this paper research has been carried out to develop a navigation technique for an autonomous robot to work in a real world environment, which should be capable of identifying and avoiding obstacles, specifically in a very busy demanding environment. In this paper better technique is develop in navigating mobile robot in above mention environment. The action and reaction of the robot is addressed by fuzzy logic control system. The input fuzzy members are turn angle between the robot head and the target, distance of the obstacles present all around the robot (left, right, and front, back). The presented FLC for navigation of robot has been applied in all complex and adverse environment. But the performance of the controller could be adjusted if FLC is well designed and compare with conventional controller.

In a related work presented in [12], the dynamic control of parallel wheeled differential drive mobile robot was considered. The dynamic model is composed of two consecutive parts; kinematic model and equations of linear and angular torques. By transforming dynamic error equations of kinematic model to mobile coordinates, the tracking problem changes to stabilization. Controller is designed in two consecutive parts: in the first part kinematic stabilization is developed using nonlinear control laws, in the second one ,acceleration rate control has been used for Exponential stabilization of linear and angular velocities. Uncertainties in the parameters of dynamic model (mass and inertia) have been compensated using model reference adaptive control. By introducing appropriate Lyapunov functions asymptotic stability of state variables and stability of system is guaranteed. The distinctive property of the proposed controller is its robustness of performance in the presence of uncertainties. Simulations illustrate quality and efficiency of this method [12]. A better result could be archived if an intelligent controller was incorporated and compare with any of conventional controller.

In this study the effect of uncertain parameters of dynamic model on system performance is considered. It’s shown that the suggested method based on adaptive control can save the closed loop performance vis-à-vis changing parameters of mass and inertia of robot. In addition, the distinctive simplicity of the proposed controller leads to the possibility of adjusting the parameters to achieve the desired performance including tracking error and control signals. These properties are especially obtained by this dynamic controller. Dynamic model is divided into two consecutive parts. By using simple control structures for each part, the effect of uncertain parameters is studied. With model reference adaptive control for uncertain parts of equations, stability and robustness of performance is guaranteed.

According to paper presented by [13], it addresses the design and implementation of multi-input multi-output (MIMO) fuzzy control for mobile robot. Firstly, MIMO fuzzy control is apply to track different desired trajectories. Secondly, the controller performs on robot for navigation purpose to avoid obstacles and reach defined target. The proposed MIMO fuzzy controller was investigated based on several conducted MATLAB simulation scenarios for mobile robot. The simulation results are presented to demonstrate the electiveness of that new control algorithm.

In this research, design of new MIMO fuzzy logic controller for tracking trajectory and navigation behaviour of mobile robot is presented. System has two fuzzy controllers that each of them has two inputs and two outputs for tracking task and four inputs and two outputs for autonomous navigation task. The information from vision system forms input to the controller while outputs controlling the speed of motors. The fuzzy controller is designed on MATLAB Simulink environment and Fuzzy Toolbox.

In this research, the strategy presents a desired performance as it is able to accurately follow the different designed trajectory which makes it desired for the case of working in indoor environment and decide the path planning to avoid obstacles and go to target. The simulation results are provided to illustrate the feasibility of the proposed MIMO fuzzy controller [13]. The system is complex because it carries two different FLC, to avoid this complexity a single FLC could be designed with extended number of rule bases that will cover the control area of the system. Fuzzy logic mathematical formulation that provides information about the uncertainty in a given unstructured environment, was established in [21]

As regards the corridor and wall-following navigation problem, some control algorithms based on artificial vision have been proposed. In [22], image processing is used to detect perspective lines to guide the robot along the centre axis of the corridor. In [23], two lateral cameras mounted on the robot are used, and the optical flow is computed to compare the apparent image velocity on both cameras in order to control robot motion. In a paper presented by [24] and [25], one camera is used to drive the robot along the corridor axis or to follow a wall, by using optic flow computation and its temporal derivatives. In [26], a globally stable control algorithm for wall-following based on incremental encoders and one sonar sensor is developed. In [27], a theoretical model of a fuzzy based reactive controller for a non holonomic mobile robot is developed. In [28], an ultrasonic sensor is used to steer an autonomous robot along a concrete path using its edged as a continuous landmark. In [29], a corridor navigation and wall following stable control for sonar-based mobile robot was presented.

A control strategy based on an emergency surveillance and situational awareness in an environment without obstacles, together with individual wheel slippage controllers is presented [30]. Also, a control strategy that assures navigation of cooperative robots in a certain formation is presented in [31] and [32]. The formation of robots is assured throughout the movement in the environment by a spring damper structure. Also, there is a fuzzy approach in controlling the formation in [33], and the results are provided in an environment with no obstacles. The study from [34] reveals an approach where the robots are moving in formation but the shape of the formation of the robots towards each other is not defined. In another paper presented in [37], a tracking controller for the dynamic model of unicycle mobile robot by integrating a kinematic controller and a torque controller based on Fuzzy Logic Theory was developed. Computer simulations are presented confirming the performance of the tracking controller and its application to different navigation problems; Computer simulation results demonstrated that the controller can achieve the said objectives but the performance of the controller could be modified by designing and incorporating a PID controller into the unicycle robot system.

2.4 PID

According to paper presented in [4], the study of performance in terms of time response specifications of a PD –type FLC and a general PD controller was demonstrated. According to [4], the design of fuzzy logic controller doesn't require previous knowledge on system characteristic equation as PD Controller; better result could be archived by comparing the performance of PD-type FLC and PID controller. Fuzzy logic controllers, so called, intelligent control function, represent much closely human thinking and natural language than logical control system used by PD control

In another paper presented by [14], it presents a unified dynamic modelling framework for differential-drive mobile robots (DDMR). Two formulations for mobile robot dynamics are developed; one is based on Lagrangian mechanics, and the other on Newton-Euler mechanics. Major difficulties experienced when modelling non-holonomic systems in both methods are illustrated and design procedures are outlined. It is shown that the two formulations are mathematically equivalent providing a check on their consistency. The presented work leads to an improved understanding of differential drive mobile robot dynamics, which will assist engineering students and researchers in the modelling and design of suitable controllers for DDMR navigation and trajectory tracking [14]. This paper has presented a detailed derivation of the dynamic model of a differential-drive mobile robot using the Lagrange and Newton-Euler methods. They were shown to be mathematically equivalent providing a check on their consistency. The equations of motion of DC motors actuators were also added to form the complete dynamic model of the DDMR. The research could have extended by also considering the kinematic robot model incorporated with FLC and PID controller respectively. In a similar work carried out in [18], it was demonstrated in the research that a mobile robot motion control is simplified to a DC motor motion control that may include gear system and the simplest and widespread approach to control the mobile robot motion is the differential drive style, it consists of two in-lines with each a DC motor. Both DC motors are independently powered so the desired movements will rely on how these two DC motors are commanded. The design, model and control of Mechatronics mobile robotic system is presented in this paper. The developed robotic system is intended for research purposes as well as for educational process. The model of proposed mobile robot was created and verified using MATLAB Simulink software [18]. But in this research, the limitation is base on the mechatronic design of two wheel mobile robot without considering the specified controller of the system, better performance could be archived by proper design of FLC and compare the result with PID controller for optimality.

According to [35], a comparison between fuzzy logic controller and proportional controller for the autonomous mobile robot was investigated, from the results obtained, it was demonstrated that a controller should be selected according to the constraints posed by a particular problem. For a small steady state error and to reduce the overshoot in the system, then FLC with sum normal fuzzy membership functions should be used. If memory size is the primary consideration then a P controller can be used as it has minimum memory requirements. If computational time is of paramount interest then a P controller or any of the FLCs with a lookup table could be used.

2.5 Differential Drive

In another paper presented in [16], it demonstrated that, the two-wheel differential drive mobile robots, are one of the simplest and most used structures in mobile robotics applications, it consists of a chassis with two fixed and in-line with each other electric motors. This paper presents new models for differential drive mobile robots and some considerations regarding design, modelling and control solutions. The presented models are to be used to help in facing the two top challenges in developing mechatronic mobile robots system; early identifying system level problems and ensuring that all design requirements are met, as well as, to simplify and accelerate Mechatronics mobile robots design process, including proper selection, analysis, integration and verification of the overall system and sub-systems performance throughout the development process [16]. New models for differential drive mobile robots and some considerations regarding design, modelling and control solutions are presented. The presented models allow designer to have maximum desired information in the form of curves and visual numerical values of all variables required in designing and controlling of a wheeled mobile robot, that can be used to face the two top challenges in developing mechatronic system; early identifying system level problems and ensuring that all design requirements are met, as well as ,to simplify and accelerate Mechatronics mobile robots design process, including proper selection, analysis, integration and verification of the overall system, as well as, sub-systems performance throughout the development process, and optimize system level performance to meet the design requirements. The testing results show the simplicity, accuracy and applicability of the proposed models in mechatronics design of mobile robots. The better performance of the whole system approach could be archived if a FLC was incorporated and compare with PID controller.

According to [17], the problem of the kinematics and dynamics of two constructional conceptions of a two wheeled mobile robot is considered. The wheeled mobile robot subjected to nonholonomic constraints moves over the inclined plane. Its trajectory consisting of the straight line and the curvilinear path described by the sinusoidal function is analyzed. The kinematic equations for arbitrarily chosen point of the system are derived by using classical equations of mechanics. Kinematic and dynamic parameters of motion from the solution of inverse kinematic and dynamic problem are obtained. Simulation results are presented to illustrate the efficiency of the approach [17]. Similarly, if the wheel mobile robot system kinematic and dynamics are incorporated with an intelligent controller like FLC and compare with any conventional controllers, better result of the approach could be archived.

In a similar research presented in [41], this article demonstrated the strategy for navigation of a wheeled mobile robot in unstructured environments with obstacles. The vehicle has two independent wheels to control the angular velocity. This article presents modelling, control strategies and simulation results of the motion of wheeled mobile robots. Kinematics model for wheeled mobile robots; there are two identical wheel of the mobile robot. Fuzzy logic strategy has a modular structure that can be extended very easily to incorporate new behaviours. Mobile robot navigation strategies using fuzzy logic have major advantages over analytical methods. Simulation results recommends fuzzy logic controller for the wheeled mobile robot motion in unstructured environments (obstacle avoidance behaviour and velocity control of vehicle), but a better result could be attained if the performance of the said controller is compared with a conventional controller in this case PID.

2.6 Inverse Kinematic

The model of mobile robot with divided chassis was investigated in [39], it demonstrated the designing and constructing a four-wheel chassis, which will possess better negotiability of diverse terrain. Analysis is a used concept of chassis motion control for mechatronic systems on the principle of differential wheel control for the task of active tracking of planned chassis path. A model is also required for examining behaviour of chassis on diverse terrain, for examining the influence of dimensions on chassis behaviour during crossing over roughness of terrain, the outcome of this research could have been better if the number of wheels of the robot are limited to only two and also for better simulation results, a well designed intelligent controller alongside the conventional counterpart could have incorporated into the robot system.

Position and orientation control of a two wheel mobile differentially driven non-holonomic mobile robot was investigated in [40]; this paper addresses the dynamic stabilization problem of a two-wheeled differentially driven non-holonomic mobile robot. The proposed strategy is based on changing the robot control variables from position of robot along x and y axes to linear displacement. It was demonstrated in this research that using this model, the nonholonomic constraints disappeared and it illustrated that the linear control theory can be used to design the robot controllers. This control strategy only needs the robot localization (x, y, θ), not requiring any velocity measurement or estimation. The complete derivation of the control strategy and some simulated results are presented, but the propose strategy of changing the robot control variables could be enhanced by proper design of fuzzy logic controller and incorporate into the same robot system.

Theoretical Aspects in Wheeled Mobile Robot Control was investigated in [42], -This work presents some considerations regarding mathematical models and control solutions for a class of mobile robots namely two-wheeled differential drive mobile robots. The closed loop control diagrams for position control and direction in tracking trajectories were developed, analyzed and included in this research. Afterwards, for these control solutions, the paper presents therefore some analyses regarding the stability for different type of inputs and alternative experiments to evaluate performances on typical test trajectories. Direct and inverse Kinematic models for this class of mobile robots are also included. Finally, to evaluate the control performances, some experimental and comparative results on complex trajectories are so indicated. But to reduce the complexity of the whole system being the system has two castor wheels and lots number of robots, there is need to limit the number of castor wheels and robots to only which will bring a better stability, also for better performance evaluation of typical test trajectories, a well comparison and design of an intelligent alongside conventional controllers could have done to the whole system.

. Inverse kinematic models for mobile manipulators were presented in [38], in this paper various designing and fabricating aspects of a 4 - DOF manipulator has been described briefly. With reference to many available manipulators and mobile platforms in market, a practical design for the mobile manipulator has been perceived and computer aided designing tools like CATIA and AutoCAD are used. Theoretical analysis of the inverse kinematics was carried out to know the joint variables of the manipulator and robot steering angle for the mobile platform (chassis). Finally, comparison has been performed in between the theoretical result obtained from the current analysis with the experimental results of a fabricated real mobile manipulator (4 DOF), for proper control analysis and application the results obtained could be modified by designing an intelligent controller alongside conventional one and finally compare the performance of each from the various responses obtained.

2.7 Different Type of Robot

A mobile robot could be modelled in numerous ways, but the most important factor for defining the model would be the application and the complexity involved. The mobile robot designed in this work is a wheeled robot intended for indoor use as opposed to other types (legged, airborne, and submersible mobile robots). This robot type is the easiest to model, control, and build. There are various behaviours that could be modelled, like wall following, collision avoidance, corridor following, goal seeking, adaptive goal seeking, etc.

Various control techniques have been proposed and are being researched. The control strategies of mobile robots can be divided into open loop and closed loop feedback strategies. In open loop control, the inputs to the mobile robots (velocities or torques) are calculated beforehand, from the knowledge of the initial and end position (and of the desired path between them in the case of path following). This strategy cannot compensate for disturbances and model errors. Closed loop strategies, however, may give the required compensation since the inputs are functions of the actual state of the system and not only of the initial and end points. Therefore disturbances and errors causing deviations from the predicted state are compensated by the use of the inputs. Of the many available closed loop control systems, including P (proportional) control, PI (proportional integral) control, and

PID (proportional integral derivative) control, fuzzy logic control was selected as it was easiest to implement for a highly nonlinear robot model.

2.8 Modelling of Two Wheel Mobile Robot

According to paper presented in [45], this article focuses on mathematical modelling of mobile robot with differentially driven two-wheel chassis. The derivation of kinematic model is based on holonomic constraints for its wheels movement, that are expressed through geometric transformations between robot's local coordinate system and the global coordinate system, in which the robot is moving. Within the dynamics derived using the Newton's laws, the friction between the contact surfaces of wheels and plane is also included as a generalized model. Mathematical model is implemented in the Simulink environment with internal control loop that suppress the impacts of dynamics. Conducted simulation experiments in open and closed-loop was demonstrated. The modelling would have been improved if the modelling of the robot system is attached with the DC motor model to have a complete system with actuator. In another paper presented in [46], the paper deals with the modelling and control strategies of the motion of wheeled mobile robots. The model of the vehicle has two driving wheels and the angular velocities of the two wheels are independently controlled. First, the vehicle kinematics model and the control strategies using a feed forward compensator are analyzed. Second, fuzzy reactive control of a mobile robot motion in an unknown environment with obstacles is proposed. Finally, the mobile robot simulation is illustrated. The modelling of two wheel mobile robot based on dynamic behaviour is presented in [47], this Paper deals with dynamic mathematical model of an ideal differentially steered drive system (mobile robot) planar motion. The aim is to create model that describes trajectory of a robot's arbitrary point. The trajectory depends on supply voltage of both drive motors. Selected point trajectory recompilation to trajectories of wheels contact points with plane of motion is a part of the model, too. The dynamic behaviour of engines and chassis, form of coupling between engines and wheels and basic geometric dimensions are taken into account. The application of Newton-Euler Method was used for mobile robot model.

Dynamic modelling of Differential-Drive mobile robot using Lagrange and Newton-Euler methodologies are presented in [14], this paper presents a unified dynamic modelling framework for differential-drive mobile robots (DDMR). Two formulations for mobile robot dynamics are developed; one is based on Lagrangian mechanics, and the other on Newton-Euler mechanics. Major difficulties experienced when modelling non-holonomic systems in both methods are illustrated and design procedures are outlined. It is shown that the two formulations are mathematically equivalent providing a check on their consistency. The presented work leads to an improved understanding of differential drive mobile robot dynamics, which will assist engineering students and researchers in the modelling and design of suitable controllers for DDMR navigation and trajectory tracking.

In this dissertation, the modelling of two wheel mobile robot will focus on the kinematic methodology and is segmented into two parts; kinematic modelling of two wheel mobile robot and the modelling of an actuator (PMDC) motor, finally the two separated model are merged together to have a complete model of the mobile robot system.

2.9 Two Wheel Mobile Robot

Two wheel mobile robots is a mehatronic system that consists of two independent driving wheels which are actuated by separated PMDC servo motors. It has a castor wheel used for the stability of the robot when navigating within its environment. The interaction between the robot and its environment is archived using inbuilt sensors e.g. proximity and ultrasonic sensors, just to mention few.

2.10 Robotic Wheel

An idealized rolling wheel is shown in Figure 2.1. The wheel is free to rotate about its axis (y axis). The robot exhibits preferential rolling motion in one direction (x axis) and a certain amount of lateral slip. For lower velocities, rolling motion is dominant and slipping can be neglected

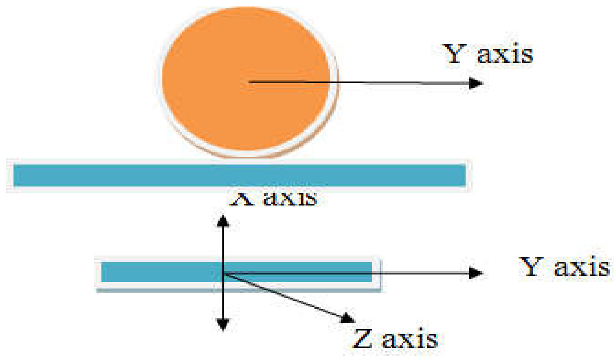

Fig 2.1: idealized rolling wheel [13]

2.11 Conclusion

In this chapter, the details literature review carried out on robotic system by different researchers are discussed which focused on advantages and disadvantages of each and also provide the possible solutions to the shortcomings indicated in each research. Different type of robot, inverse kinematic and the concept of robotic wheel are also discussed. In the next chapter, the modelling and control approach of two wheels robot system are discussed.

CHAPTER THREE

Modelling and Control Approach

3.1 Introduction

In this chapter the mathematical model of differential drive two wheel mobile robots alongside the model of an actuator (PMDC) are discussed. In section 3.3, the differential drive of wheels is discussed. In section 3.4, equations defining the robot are discussed while 3.5 describe the mathematical model permanent magnet DC motor was discussed while in section 3.6 focuses on fuzzy logic controller design and its terminologies.

3.2 Mathematical Robot Model

This section describes the kinematics and dynamic equations of the wheeled mobile robot of the unicycle type and formulates the problem of controlling it to a point with a desired orientation. The vehicle has two identical parallel, non-deformable rear wheels which are controlled by two independent motors, and a steering front wheel (castor wheel). It is assumed that the plane of each wheel is perpendicular to the ground and the contact between the wheels and the ground is pure rolling and non-slipping, i.e., the velocity of the centre of mass of the robot is orthogonal to the rear wheels' axis. It is further assumed that the masses and inertias of the wheels are negligible and that the centre of mass of the mobile robot is located in the middle of the axis connecting the rear wheels.

3.3 Differential Drive

Kinematics is the study of the mathematics of motion without considering the forces that affect the motion. It deals with the geometric relationships that govern the system. It develops a relationship between control parameters and the behaviour of a system in space.

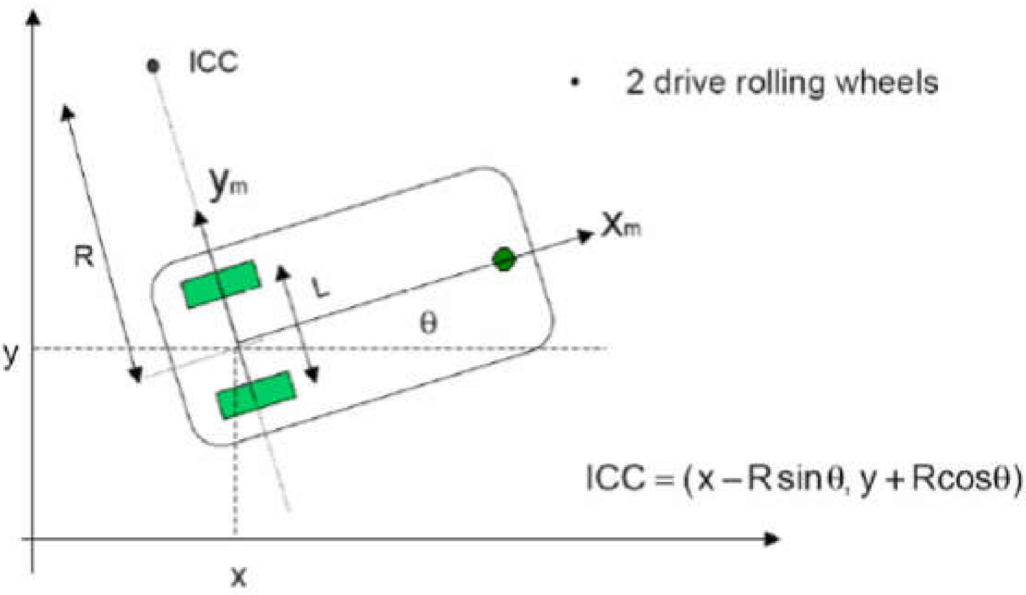

Fig.3.1 Kinematic model of the robot [35] [36]

Figure 3.1 above illustrated the kinematic model of the robot considered to be on the moving frame Cartesian co-ordinate; it has two rear driving wheels separated by distance L, and a castor wheel used for stability. The particular point where robot position itself in order to attain stability is described as instantaneous centre of curvature ICC, and is the perpendicular distance between the component of robot linear velocities along x and y axes. The instantaneous radius of curvature of the robot trajectory which is the distance between the instantaneous centre of curvature ICC, and the mid- point of the two rear wheels is described as R. Y_m and X_m are the linear velocities of the robot along y and x axes respectively. According to the figure 1, since the robot is assumed to be moving on the Cartesian plane and turning towards right direction, therefore, X_m is assumed to be the overall linear velocity of the robot which is to be resolved either to y or x axes respectively using the orientation angle Ɵ.

3.4 Equations Defining the Robot

The first step to a kinematic model of the robot is to consider the motions of individual wheels. To test the algorithm, a simple model of robot is chosen. The robot has a differential drive system with two independent wheels and a caster for stability. The first constraint enforces the concept of rolling contact that the wheel must roll when motion takes place in the appropriate direction. The second constraint enforces the concept of no lateral slippage, that the wheels have pure rolling and non-slipping conditions during the motion in wheel plane. In this dissertation the kinematic model of the mobile robot was adopted from [13][16] [18][35] and described as follows:

The wheel parameters are:

r= wheel radius

v= wheel linear velocity

w= wheel angular velocity

Vr(t)= linear velocity of right wheel

Vl(t)= linear velocity of left wheel

Wr(t)= angular velocity of right wheel

Wl(t)= angular velocity of left wheel

r= nominal radius of each wheel

L= distance between the two wheels

R= instantaneous curvature radius of the robot trajectory, relative to the mid-point of the wheel axis

ICC = Instantaneous Centre of Curvature

R-(L/2) = Curvature radius of trajectory described by left wheel

R+ (L/2) = Curvature radius of trajectory described by right wheel

With respect to ICC the angular velocity of the robot is given as follows:

$$w(t) = Vr(t) / \left(R + \frac{L}{2} \right) \tag{3.1}$$

$$w(t) = Vl(t) / \left(R - \frac{L}{2} \right) \tag{3.2}$$

$$w(t) = \frac{Vr(t) - Vl(t)}{L} \tag{3.3}$$

$$R = \frac{L}{2} \left(\frac{Vr(t) + Vl(t)}{Vr(t) - Vl(t)} \right) \tag{3.4}$$

The above equations were derived according to adopted model [13][16][18][35].

Therefore the linear velocity of the robot is given by:

$$. \quad v(t) = w(t) * R = \frac{Vr(t) - Vl(t)}{L} * \left(\frac{L}{2} \right) [Vr(t) + Vl(t)] / [Vr(t) - Vl(t)]$$

Therefore,

$$V(t) = \frac{1}{2} \left[Vr(t) + Vl(t) \right] \tag{3.5}$$

Now, by considering the robot in the moving frame:

$q = [x \; y \; \Theta]^T$ Robot position in the inertial frame (3.6)

$q = [x\ y\ \Theta]^T$ Robot position in the moving frame (3.7)

$q = [Vx\ Vy\ w\ ]^T$ Same as (3.7) above

Where:

$Vy = y,$ Component of moving velocity along y-axis;

$Vx = x$ Component of moving velocity along x-axis; (3.8)

And $w = \frac{d\Theta}{dt}$. Orientation angle of the robot moving frame.

Now by resolving the velocities of the robot moving frame into x and y components, one has:

$\sin\Theta = \frac{Vy(t)}{V(t)}$ (3.9)

Implies, $Vy = V\sin\Theta$

Also, $\cos\Theta = \frac{Vx(t)}{V(t)}$ (3.10)

Implies, $Vx(t) = \mathrm{V(t)}\cos\Theta$

But,$w = \Theta,$

Therefore,

$$y = V(t)\sin\Theta(t)$$

$$x(t) = \mathrm{V(t)}\cos\Theta\,(t)$$

$$\Theta = w(t) \qquad (3.11)$$

By substituting (3.3) and (3.5) into (3.11), yields

$$\dot{x}(t) = \frac{1}{2}\mathrm{Vr}(\mathrm{t})\cos\frac{1}{2}\mathrm{Vr}(\mathrm{t})\cos\theta(t) + \frac{1}{2}\mathrm{Vl}(\mathrm{t})\cos\frac{1}{2}\mathrm{Vl}(\mathrm{t})\cos\theta(t)$$

$$\dot{y}(t) = \frac{1}{2}\mathrm{Vr}(\mathrm{t})\sin\frac{1}{2}\mathrm{Vr}(\mathrm{t})\sin\theta(t) + \frac{1}{2}\mathrm{Vl}(\mathrm{t})\sin\frac{1}{2}\mathrm{Vl}(\mathrm{t})\sin\theta(t)$$

$$\dot{\theta}(t) = \frac{Vr(t)}{L} - \frac{Vl(t)}{L} \qquad (3.12)$$

Now in matrix form,

$$\begin{bmatrix} x \\ y \\ \Theta \end{bmatrix} = \begin{matrix} \frac{1}{2}\cos\Theta & \frac{1}{2}\cos\Theta \\ \frac{1}{2}\sin\Theta & \frac{1}{2}\sin\Theta \\ \frac{1}{L} & \frac{1}{L} \end{matrix} \begin{bmatrix} Vr \\ Vl \end{bmatrix} \qquad (3.13)$$

Generally,

$$Vx = \frac{dx}{dt}\ implies\ dx = Vxdt$$

$$Vy = \frac{dy}{dt}\ implies\ dy = Vydt$$

$$\frac{d\Theta}{dt} = w\ implies\ d\Theta = wdt \qquad (3.14)$$

$$\Theta(t) = S(q)\ (t) \qquad (3.15)$$

3.5 Inverse Kinematic Model of Mobile Robot

In general, we can describe the position of a robot capable of moving in a particular direction at a given velocity, base on the two components of velocities V(t), the travelled distance in each direction can be calculated as:

Integrating (3.11) yields:

$$x(t) = \int V(t) \cos \Theta(t) dt$$

$$y(t) = \int V(t) \sin \Theta(\mathrm{t})\, dt$$

$$\Theta(t) = \int w(t) dt \qquad (3.16)$$

Where the right hand of the first equation in (3.16) represent the component of robot linear velocity along x direction, right hand side of the second equation represent the robot linear velocity along y direction and right hand side of the third equation represent the robot angular velocity.

Substituting equation (3.5) and (3.3) into (3.16), and at any given time t, the equations of the robot position become:

$$x(t) = \frac{1}{2} \int_0^t [V_r(t) + V_l\,(t)] \cos\,[\theta(t)] dt$$

$$y(t) = \frac{1}{2} \int_0^t [V_r(t) + V_l\,(t)] \sin\,[\theta(t)] dt$$

$$\theta(t) = \frac{1}{L} \int_0^t [V_r\,(t) \quad V_l(t)] dt \qquad (X)$$

Equation *X* is used to build the model of a two wheel mobile robot in a Matlab/Simulink environment in terms of robot positions along x any directions.

Equation in matrix form as shown in (3.13) represent the kinematic model of a differential drive mobile robot, these are the equations that are used to build a model of the robot. These equations were used to simulate the robot in MATLAB Simulink. The fuzzy logic controller was tested and fine tuned on this model for optimum results, as well as compared with other controllers.

3.6 Mathematical Model of Permanent Magnet DC Motor (PMDC)

The mobile robot motion control is simplified to a PMDC motor motion control. The PMDC motor is an example of electromechanical systems with electrical and mechanical components, a simplified equivalent representation of PMDC motor two components are shown in Figure (3.2). The equations of motion for the robot will consider the simple case where the robot can move forward and reverse and turns to the right and left directions, this is archived since differential drive wheels are used, and each rear wheel is controlled independently.

Consider the block diagram of a PMDC motor in Figure 3.2. The simplified mathematical dynamic equation is obtained from the block diagram of PMDC motor using Newton's law of motion [47].

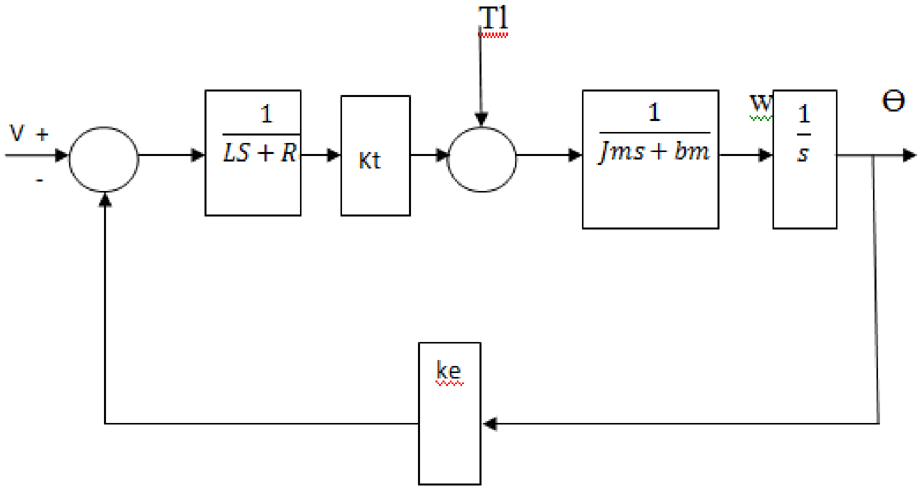

Fig 3.2 Block diagram of PMDC motor

Applying a voltage to motor coils, produces a torque in the armature. The torque developed by the motor, T_m is related to the armature current, $I_a$by a torque constant K_t and given by the following equation,

$$Motor\ Torque = T_m$$

Implies that, $T_m = K_t I_a$ (3.17)

The back electromotive force, EMF voltage, e_a is induced by the rotation of the armature windings in the fixed magnetic. The EMF is related to the motor shaft angular speed, w_m by a linear relation given by:

$$e_a(t) = K_b \frac{d\theta m(t)}{dt} = K_b w_m \quad (3.18)$$

Where $K_b$is the motor back EMF constant,

For $w_m = \frac{d\theta m(t)}{dt}$

Based on the Newton's law combined with the Kirchhoff's law, the differential equations describing electric characteristics of PMDC motor can be derived; Applying Kirchhoff's law around the electrical loop by summing voltages gives:

$$\sum V = V_{in} \quad V_r \quad V_L \quad EMF = 0 \tag{3.19}$$

Implies that

$$V_{in} = V_r + V_L + EMF$$

But $\quad V_r = R_a I_a, \ V_L = L_a \left(\frac{dI_a(t)}{dt}\right), \quad EMF = K_b \frac{d\theta(t)}{dt}$

Applying Ohm's law, substituting, rearranging and taking Laplace transform, gives the equation that describes the electrical characteristics of PMDC motor as:

$$V_{in} = R_a I_a(t) + L_a \left(\frac{dI_a(t)}{dt}\right) + K_b \frac{d\theta(t)}{dt} \tag{3.20}$$

Taking Laplace transform of both side

$$V_{in}(s) = R_a I(s) + sL_a I(s) + sK_b \theta(s) \tag{3.21}$$

Implies that,

$$V_{in}(s) = (R_a + sL_a)I(s) + sk_b\theta(s)$$

$$(R_a + sL_a)I(s) = V_{in}(s) \quad sk_b\theta(s) \tag{3.22}$$

The torque, developed by motor, produces an angular velocity, ω= dθ/dt, according to the inertia J and damping friction, b, of the motor and load. Performing the energy balance on the PMDC motor system; the sum of the torques must equal zero, this gives:

$$\sum T = J_a = J\frac{d^2\Theta}{dt^2} \tag{3.23}$$

Implies $T_e \quad T_a \quad T_w \quad T_{emf} = 0$

But, $T_e = K_t I_a, T_a = J_m \frac{d^2\Theta}{dt^2}$ $and\ T_w = b_m \frac{d\Theta}{dt}$

Substituting the above values in open loop PMDC motor system without load attached, where the change in T_{motor} is zero gives:

$$K_t I_a \quad T_{load} \quad J_m \frac{d^2\Theta}{dt^2} \quad b_m \frac{d\Theta}{dt} \tag{3.24}$$

Taking Laplace transform and re-arranging, gives:

$$K_t I(s) = [J_m s^2 + b_m s]\Theta(s) \tag{3.25}$$

The electrical and mechanical PMDC motor components are coupled to each other through an algebraic torque equation given by (3.25). To derive the PMDC motor transfer function, there is need to rearrange (3.22) describing electrical characteristics of PMDC, such that only I(s) on the right side, then substitute this value of I(s) in (3.25) describing PMDC mechanical characteristics, this gives:

$$[L_a s + R_a]I(s) = V_{in}(s) \quad sk_b\theta(s)$$

Implies, $$I(s) = \frac{V_{in}(s) - sK_b\theta(s)}{[L_a s + R_a]} \tag{3.26}$$

Substituting (3.26) into (3.25) above yield,

$$K_t\left[\frac{V_{in}(s) \quad sk_b\theta(s)}{[L_a s + R_a]}\right] = \left[J_m s^2 \quad b_m s\right]\Theta(s) \tag{3.27}$$

Implies, $K_t\left(V_{in}(s) \quad sk_b\theta(s)\right) = [L_a s + R_a]\left[J_m s^2 \quad b_m s\right]\Theta(s)$

Now by re-arranging equation (3.27) and assuming K_t=K_b=K the transfer function of PMDC will be:

$$\frac{\theta(S)}{V_{in}} = \frac{K}{(L_a S + R_a)(J_m S^2 + b_m S) + SK^2} \qquad (3.28)$$

Table 3.1 summarises the approximate values of PMDC motor parameters used and these values are substituted in equation (3.28) to get the complete transfer function of PMDC motor [10].

Table 3.1 Parameters of PMDC motor [10]

Symbol	**Description**	**Value**	**Unit**
R_a	Armature resistance	4.31	Ohm(Ω)
L_a	Armature inductance	2.758×10^{-5}	H
K_t=K_b=K	Torque constant	36.8	mNm/A
J_m	Rotor inertia	11×10^{-6}	Kgm^2
V_{dc}	Rated voltage	36	V
P	Pole pairs	1	
T	Peak torque	158	mNm
B_m	Damping ratio	0.708×10^{-4}	Nms

Thus, substituting these parameter values into equation (3.28), the transfer function of PMDC motor is (3.29),

$$\frac{\theta(s)}{V_{in}(s)} = \frac{7\ 7.2307\ 6}{s^2+6.43\ 64s} \quad (3.29)$$

For simulation purpose, equation (3.29) is used to build the model of a PMDC motor.

3.7 COMBINED MODEL OF AN ACTUATOR (PMDC) WITH MOBILE ROBOT

Since the output of an actuator (PMDC) which is the angular position is served as the input to the mobile robot system, therefore equation (3.12) in section 3.4 and (3.29) in section 3.5 are combined together to form a complete system as shown in figure 3.3.

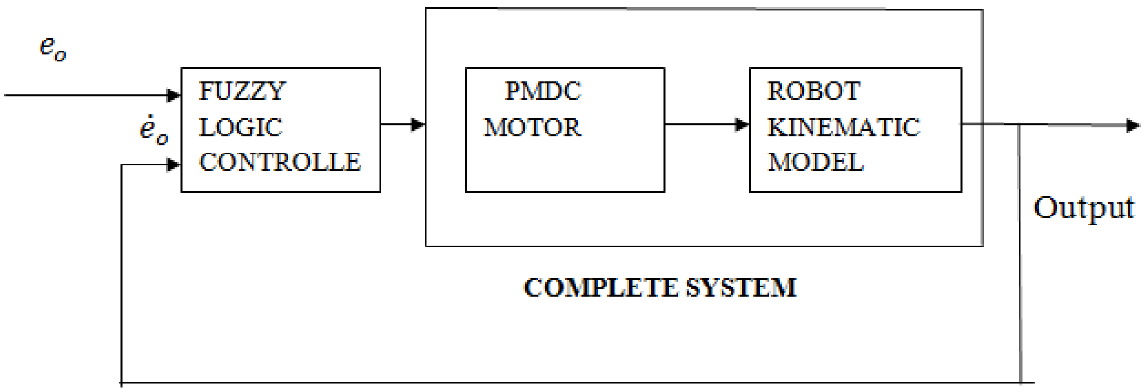

Fig 3.3: Block diagram of the complete system

The mobile robot model is built in the Matlab/Simulink environment using equation 3.12 as shown in figure 3.4

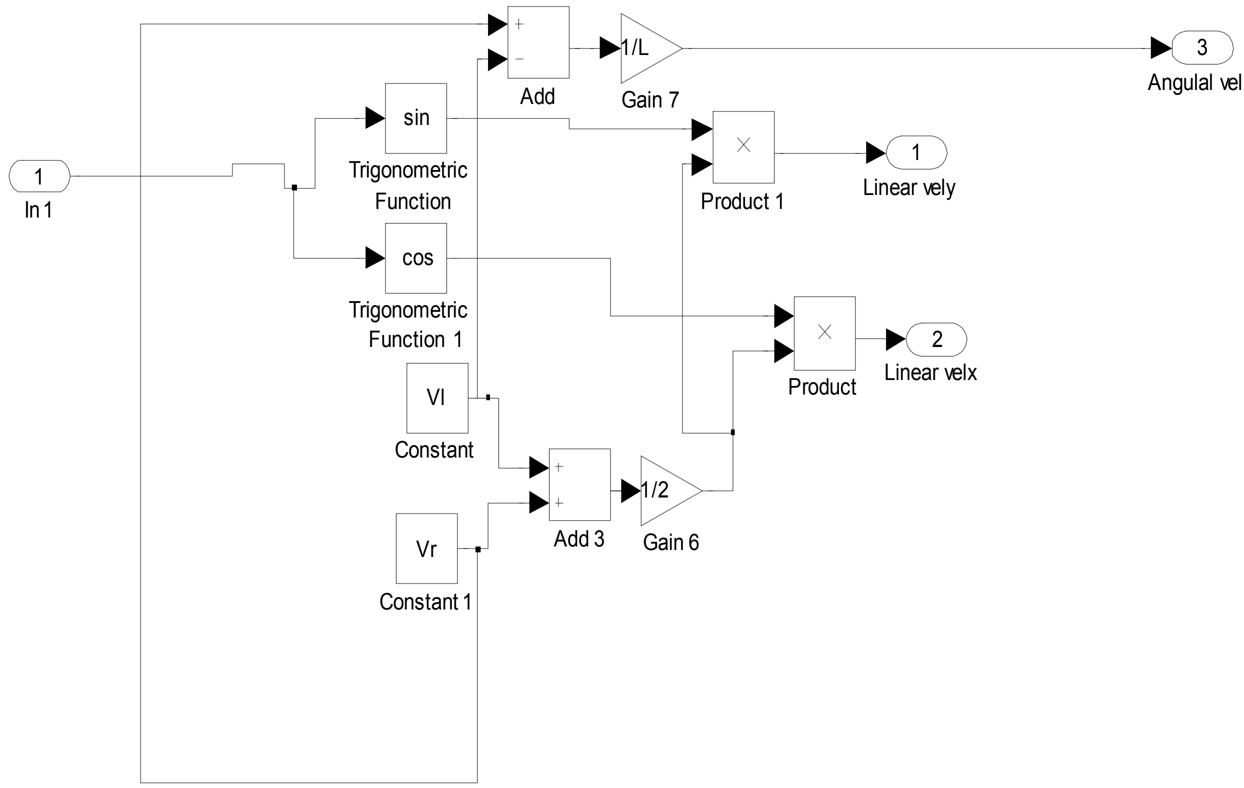

Fig 3.4: Kinematic mobile robot model

Where the input to the robot system comes from the output of PMDC motor as an actuator.

Similarly, equation (3.29) which is in the form of Laplace transform is used to built the model of PMDC motor in the Matlab/ Simulink environment as shown in figure 3.5 and is combined with the mobile robot model to produce a complete system.

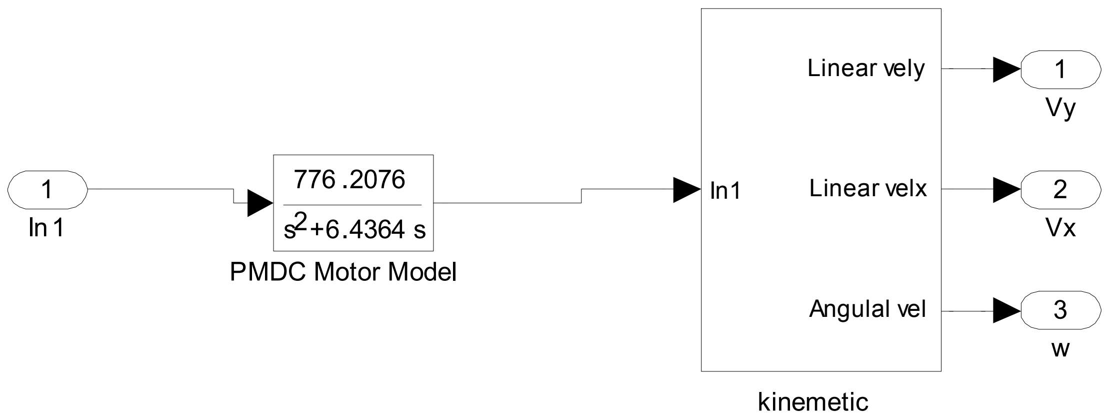

Fig 3.5: Combined model of PMDC motor and mobile robot system

3.8 Fuzzy Logic Controller (FLC) Design

There has been some published worked regarding fuzzy logic motion control. However, this area is still relatively uncharted when compared to the amount of published research regarding other methods of control.

Large systems with many rules would require very powerful and fast processors to compute in real time. The smaller the rule base, the less computational power needed. To reduce processing time, a static lookup table can be used to generate FLC control action. In some applications, that can greatly reduce processing time compared to performing fuzzy inference.

This dissertation details the FLC for the stabilisation of two wheel mobile robot for a Kinematics model. The FLC used has two inputs: error in the input and its derivatives, it also has one output which could be component of linear velocity of the robot along x-axis (v_x), component of linear velocity of the robot along y-axis (v_y), and angular speed of the robot (w), this is applied to kinematic robot model. Thus the FLC is a two input, one output system.

MATLAB'S Fuzzy Logic Toolbox [20] was used to aid in the FLC design. The toolbox contains functions, graphical user interfaces and data structures that allow the user to quickly design, test, simulate and modify a fuzzy inference system.

The output of the FLC is the control signal that fed into the whole system; input linguistic variables are angle error and its derivatives. Thus the input linguistic variables are 'negative big' (NB), 'negative small' (NS), 'zero' (Z), 'positive small' (PS), and 'positive big' (PB), this is applied to both inputs of the FLC. Similarly, the output linguistic variables of the proposed fuzzy logic controller are, 'reduce output big' (ROB), 'reduce output medium' (ROM), 'reduce output small' (ROS), 'leave output constant' (LOC), 'increase output small' (IOS), 'increase output medium', (IOM), and 'increase output big' (IOB). All five i/p linguistic variables have been assigned five linguistic values, and all seven o/p linguistic variables have been assigned seven linguistic values. The triangular membership functions are used for their simplicity as is quite commonly done.

The numerical values range of the fuzzy logic controller design for the error input is from -1 to 1, for the error rate is from -2.7 to 2.7 respectively. Similarly, the fuzzy logic controller output ranges from -29 to 29. These are the ranges of the proposed controller numerical values used in the design.

Generating the rules for fuzzy inference system is often the most difficult step in the design process. It usually requires some expert knowledge of the plant dynamics. This knowledge could be in the form of an intuitive understanding gained from experiment, or it could come from a plant model which is then used in a computer simulation. The rule base for the FLC proposed in this study is listed in Table 3.2. Thus there are 25 total rules for the two wheels combined (combination of five inputs MF of angle error and its derivative). Of these at any instant only two given rules are fired thus making it easier to understand and debug the rules.

Table 3.2: Fuzzy rule bases

e/e	**NB**	**NS**	**Z**	**PS**	**PB**
NB	ROB	ROB	ROM	LOS	LOC
NS	ROB	ROM	ROS	LOC	IOS
Z	ROM	ROS	LOC	IOS	IOM
PS	ROS	LOC	IOS	IOM	IOB
PB	LOC	IOS	IOM	IOB	IOB

Using if –then rules there are 25 rule bases according to Table 3.2. Example of the first rule is, IF angle error is negative big and change in angle error is negative big THEN the output of the FLC is reduce output big.

Tuning an FLC is a daunting task as there are many parameters that can be adjusted. These include the rules, membership functions and any other gains within the control system. The overall FLC tuning process consists of the following two steps.

• Gross adjustment of the system is done by iteratively adjusting rules, membership functions and number of variables needed.

• Once gross tuning is accomplished, the FLC is fine tuned. This involves slight adjustments of individual membership functions and their ranges.

3.9 PID CONTROLLER DESIGN

PID controllers are commonly used to regulate the time-domain behaviour of many different types of dynamic plants [9]. The gains are to be tuned experimentally to obtain the desired overall desired response. The PID controller transfer function is given by:

$$G_{PID} = K_p + \frac{K_p}{s} + K_D = \frac{K_D s^2 + K_p s + K_I}{s} = K_D \left[s^2 + \frac{K_P}{K_D} s + \frac{K_I}{K_D} \right] \tag{3.29}$$

Where $K_p, K_{D,} and\ K_I$ are the gains of the controller with the following numerical values: $K_p = 10$, $K_D =$ 0.0001 and $K_I = 4$.

Equation 3.29 is used to design the PID controller and incorporate in the whole system, further, gain values are tuned manually to obtain desired response on different configuration setup.

3.10 Conclusion

The details mathematical modelling of two wheels mobile robot kinematic alongside PMDC motor model are presented, the kinematic equations of robot and transfer function of PMDC motor are combined together to form a complete system model, finally, the proposed FLC and PID controller are designed. Next chapter deals with the simulation of the complete system in the Matlab environment.

CHAPTER FOUR

Simulation, Results and Discussion

4.1 Introduction

In this section, the simulation results of various responses of the controllers are discussed.

4.2 Simulation of Non Linear Model with FLC

Consider the kinematic non linear model system incorporated with FLC as shown in Figure 4.1

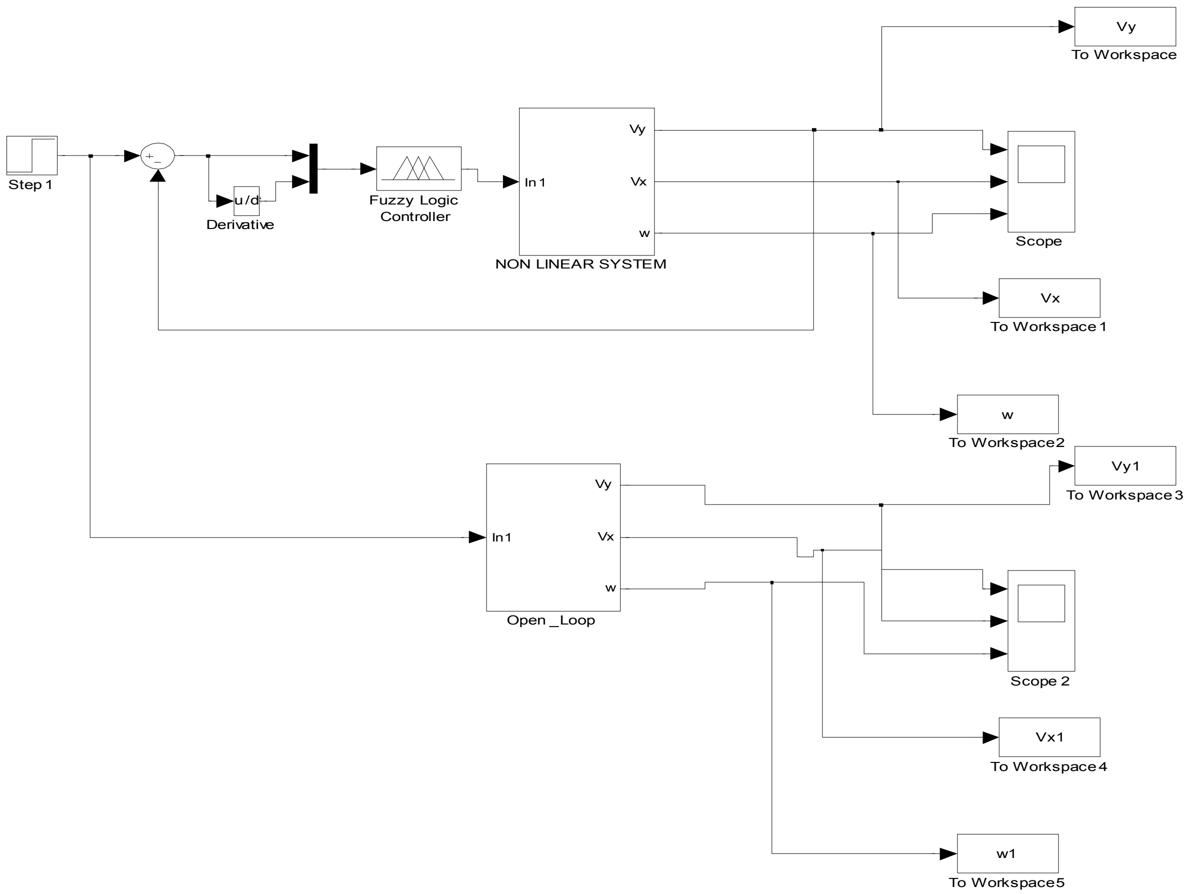

Fig 4.1: Nonlinear robot model with FLC

Figure 4.1 demonstrated the model of a two wheel mobile robot with fuzzy logic controller, the system consist of close loop and open loop subsystems. Non linear system is a complete combined robot kinematic and PMDC motor model of which each one has three output as Vx, Vy and w. The equations used to realise this model are (3.12) and (3.29) respectively.

Simulating the above model under unit step input, the results obtained for vertical linear velocity Vy, horizontal linear velocity Vx and angular speed w with FLC are presented in figure 4.2

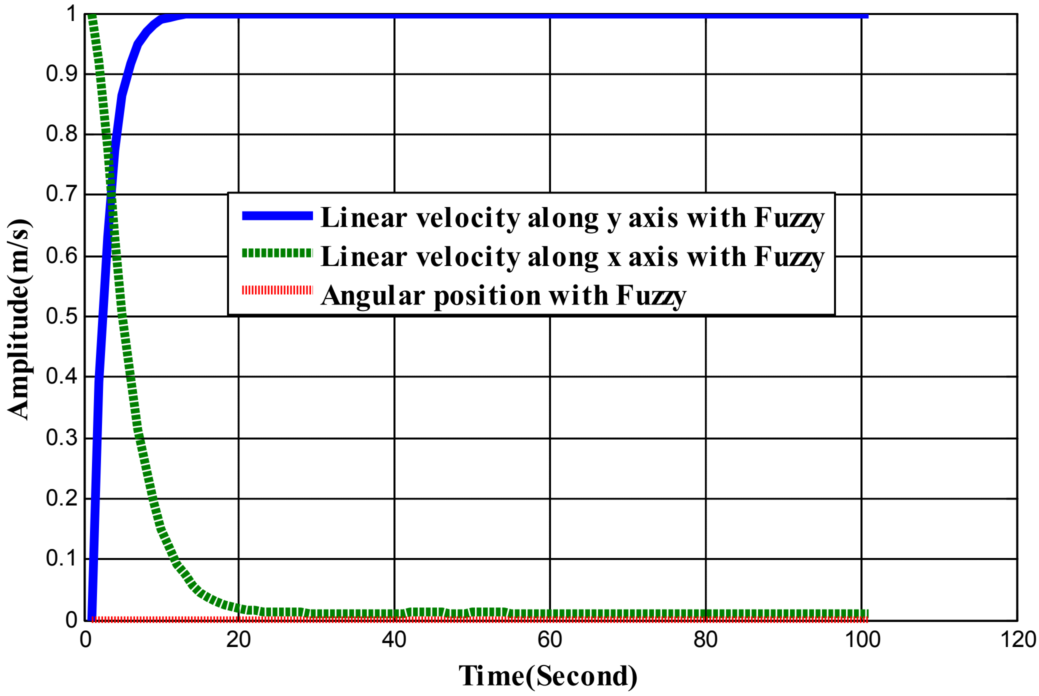

Fig 4.2: Responses of Vy, Vx and w with FLC

Where Vy and Vx are the component of robot linear velocities along Y and X axes respectively and w is the robot angular velocity and it remains zero for both open and close loop systems as shown in its response, this is as the result of dynamic behaviour of the robot described in equation (3.3) of chapter three, since the following assumption is made:

1. If Vl = Vr, robot will have forward linear motion in a straight line. R becomes in nite, and there is effectively no rotation ω is zero [44]

Note: Differential drive vehicles are very sensitive to slight changes in velocity in each of the wheels. Small errors in the relative velocities between the wheels can affect the robot trajectory. They are also very sensitive to small variations in the ground plane, and may need extra wheels (castor wheels) for support [44]

Similarly, simulating the above nonlinear model without FLC (open loop), the following results were obtained as shown in figure 4.3.

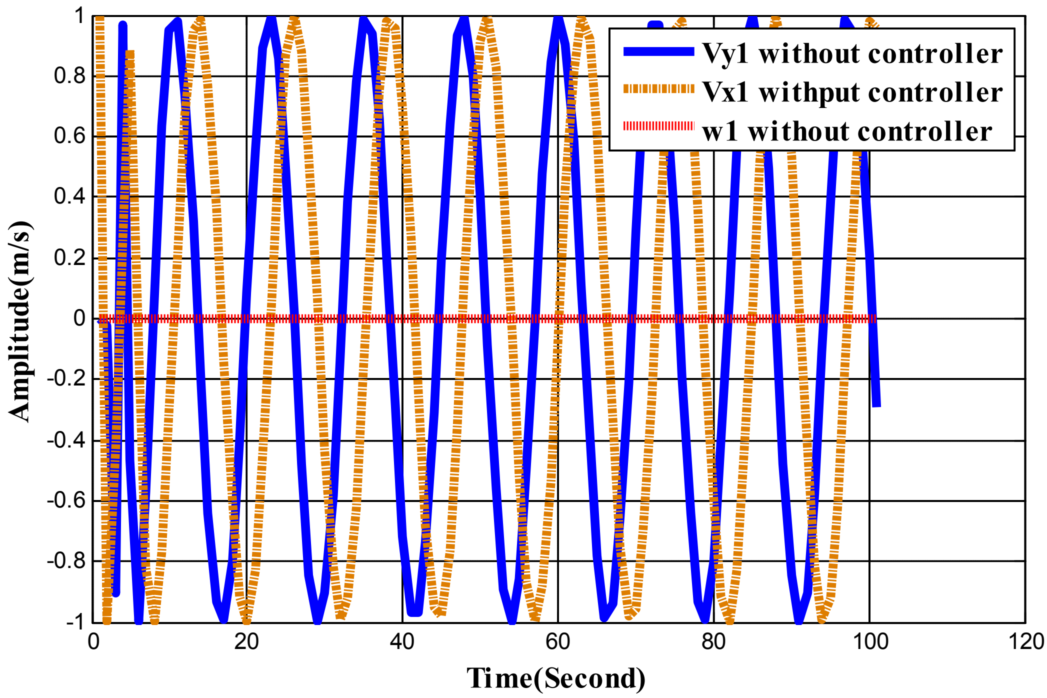

Fig 4.3: Responses of Vy1, Vx1 and w1 without FLC

Vy1 is an open loop robot linear velocity along y-axis, Vx1 is the open loop robot linear velocity along x-axis and w1 is the open loop response of robot angular velocity respectively.Vy1 is a sine wave (sinusoidal) which demonstrated the presence of sine trigonometric function shown in its robot linear velocity kinematic equation along y-axis, which resulted from the component of robot linear velocity along y axis and it started at zero then oscillating to its maximum and minimum magnitude of -1 to 1 respectively. Similarly, Vx1 is an open loop robot linear velocity along x-axis, the shape of its response demonstrated cosine wave form, this is at the result of the presence of cosine trigonometric function in its robot linear velocity which resulted from the component of robot linear velocity equation along x-axis and it started at 1 then oscillating to its maximum and minimum magnitude of -1 to +1 respectively. w is the response of robot angular velocity of which it maintained zero output as shown as blue line response in figure 4.3; this is the same as that of close loop response incorporated with either FLC or PID controllers respectively. This is as the result of assumptions made during modelling of the system where the right linear velocity was assumed to be same as left linear velocity and the robot will only move linearly along either x or y axes respectively, so overall angular velocity will remain as zero permanently [44].

4.3 Simulation of Non Linear Model with PID

Using the same simulation system configuration as shown in figure 4.1, PID controller was also designed and incorporated into the system, with 100 seconds time of simulation, the following results were obtained

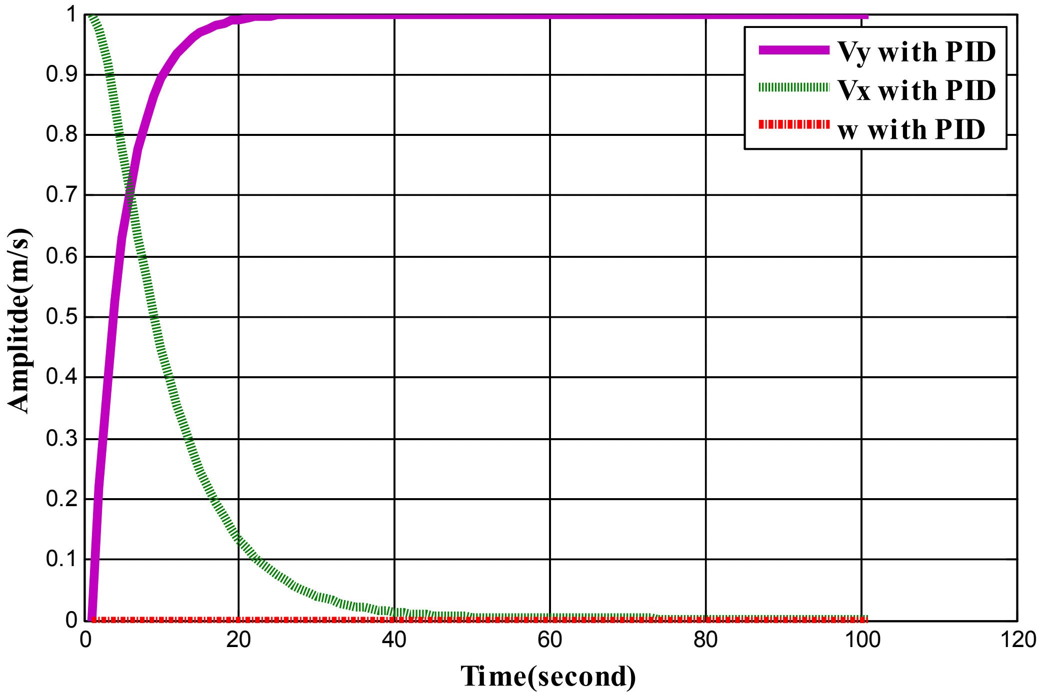

Fig 4.4: Responses of Vyp, Vxp and wp with PID controller (nonlinear model)

Where Vyp is the robot linear velocity along y axis and Vyx is the response of robot linear velocity along x axis with PID. As it was shown in its response, Vyp started at zero and settled at 1 with blue line shown, which demonstrated the behaviour of robot linear velocity moving along y-axis. Similarly, Vxp demonstrated the behaviour of robot linear velocity moving along x-axis which started at 1 and settled at zero as shown in the figure with green line, this is as the results of the two components of robot velocities.

4.4 Performance comparison between FLC and PID

The responses obtained for the robot linear motion along y axis after simulation with FLC and PID controller are plotted and demonstrated in figure 4.5.

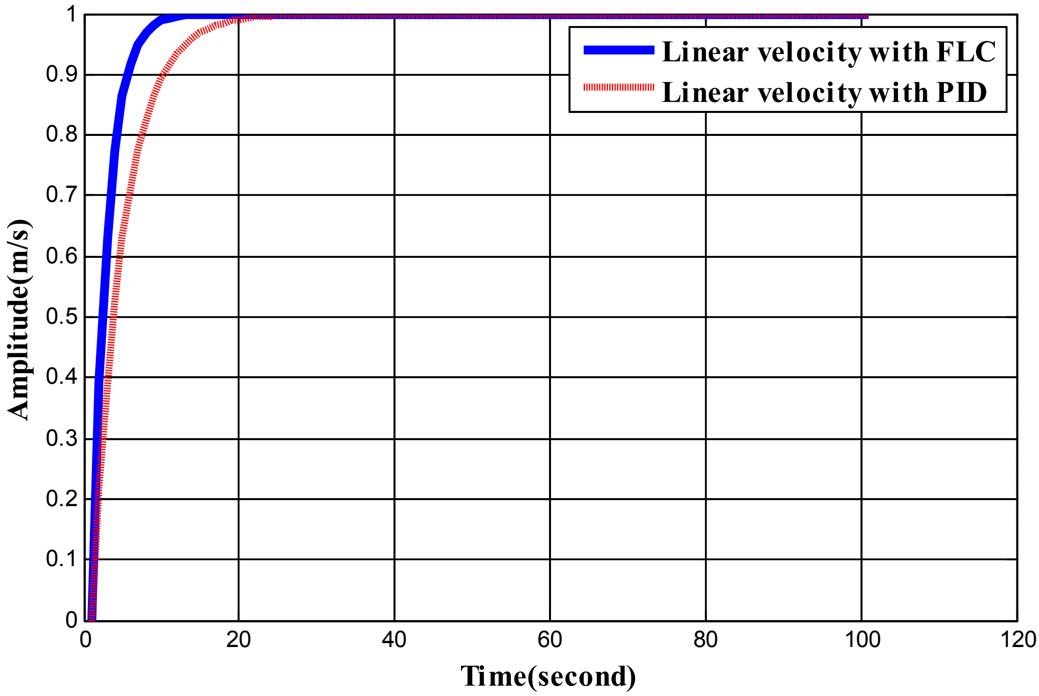

Fig.4.5: Response of Vy and Vyp with FLC and PID for non linear robot model

As shown in the figure 4.5, Vy and Vyp presented the response of robot linear velocities with FLC and PID controllers respectively. The performance comparison between the proposed controller FLC and PID using some performance indices are tabulated in Table 4.1 below.

Table 4.1: Performance comparison between PID and FLC for non linear robot model

Performance Index	**FLC**	**PID**
Rise Time	0.44 seconds	0.88 seconds
Settling Time	0.89 seconds	1.68 seconds
Overshoot	0%	0%
Steady State Error	0	0

As it was shown in Table 4.1, using some of the performance indices deduced from system response information in Matlab environment of figure 4.5, FLC demonstrated superiority than PID controller in terms of rise time and settling time of which FLC produced a rise time of 0.44seconds as compared with PID that produced 0.88seconds rise time respectively, also in terms of settling time; FLC shows superiority than PID controller as it produced 0.89seconds settling time as compared with PID of 1.68seconds respectively.

4.5 Simulation of Non Linear Model With Respect To Robot Position with FLC

Similarly, in this sub section, the results obtained for non linear model with respect to robot position are discussed. Let consider the non linear model with FLC.

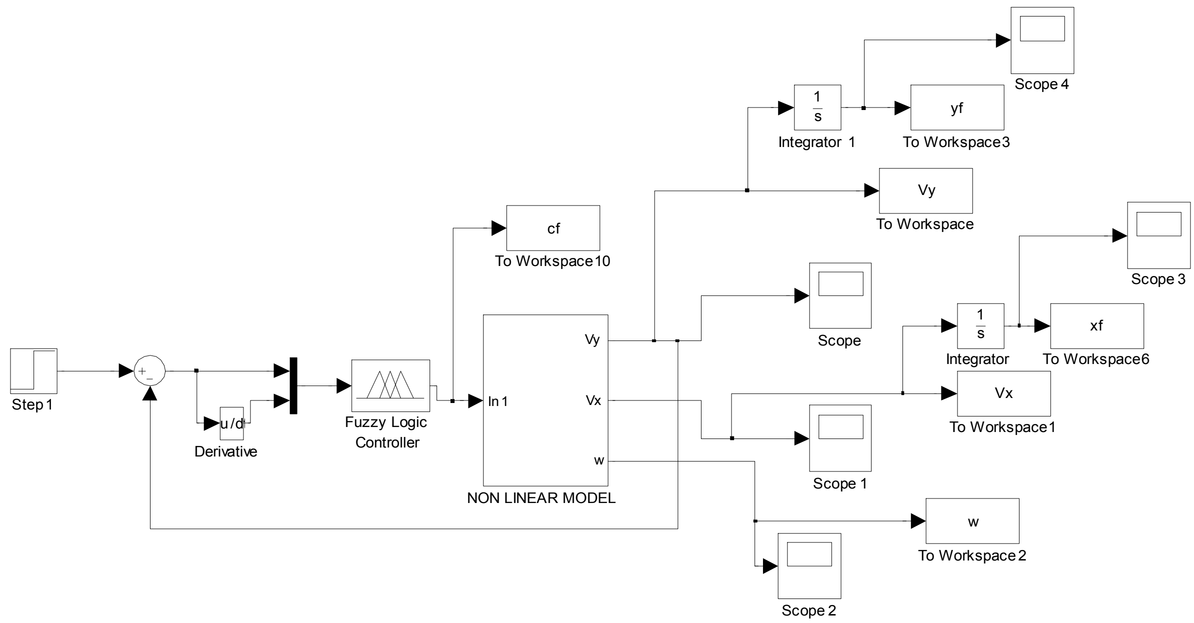

Fig 4.6: Position simulation block diagram of non linear wheel mobile robot model with FLC

Where the non linear model is a complete system comprises the PMDC and Robot kinematic model combined together as shown in figure 3.6 in chapter three. The FLC was incorporated in the system in order to control the position of mobile robot along its x-y axes.

4.6 Simulation of Non Linear Model With Respect To Robot Position with PID

In this sub section, the simulation and the results obtained for the robot position along its x-y axes are discussed.

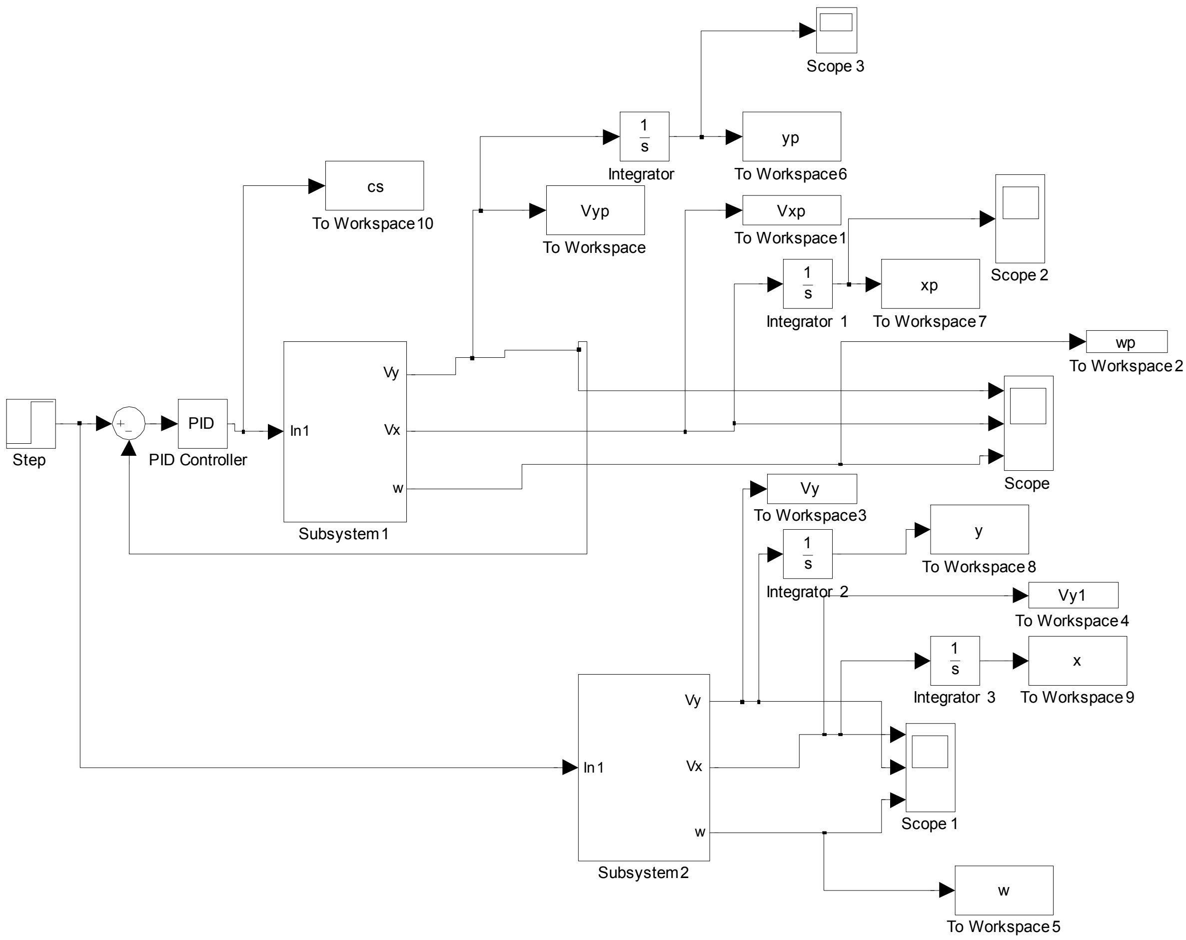

Fig 4.7: Position simulation block diagram of non linear wheel mobile robot model with PID.

The system simulation configuration consists of a close loop subsystem incorporated with FLC and PID as shown in figure 4.6 and 4.7 respectively. In order to address the inverse kinematic problem of two wheels mobile robot, the system configuration was adjusted by incorporating the integrator to the output of the non linear system as shown in figure 4.6 and 4.7 respectively. Subsystem1 and 2 are built and realised using equations (3.12) and (3.29) and also figure 3.6 in chapter three.

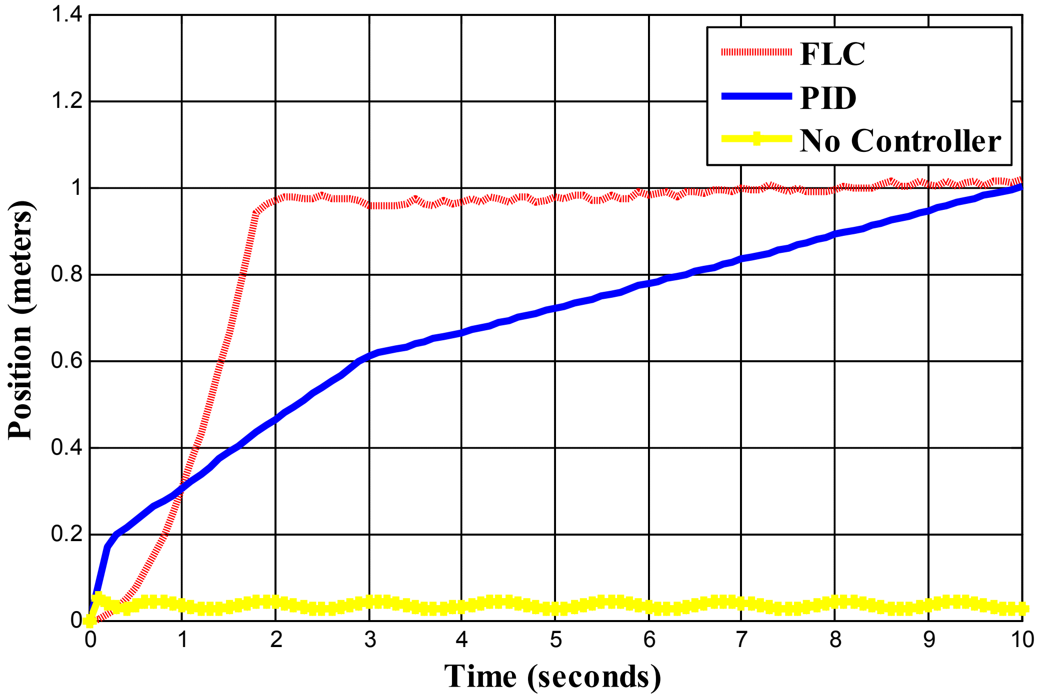

Fig 4.8: Position response of robot in terms of y-axis with FLC, PID and without controller.

The various responses of the robot position along y-axis are plotted in figure 4.8 above where the red dash line demonstrated the response of the robot position with FLC, while blue line represents the robot position with PID controller. The performance comparison between FLC and PID controller are tabulated in table 4.2 below

Table 4.2: Comparison of robot position along y-axis between FLC and PID

Performance Index	**FLC (yf)**	**PID (yp)**
Rise Time	1.20seconds	8.06seconds
Settling Time	8.53seconds	9.71seconds
Steady State Error	0.019	0

Some of the performance indexes used as shown in Table 4.2 are obtained from the system information in the Matlab/Simulink environment.

Using the performance indices of the two controllers, FLC shows superiority than PID controller in terms of rise and settling time where FLC produced a rise time of 1.2seconds as against 8.53seconds produced by PID, similarly, FLC produced a settling time of 8.53seconds as against 9.71seconds produced by PID. FLC demonstrated superiority than PID in terms of robot position along y direction.

4.7 Simulation of control signal with respect to robot moving linear velocity and position

In terms of control signal applied to each system configuration, the following simulation results are obtained:

First let consider the control signal produced by FLC in terms of robot position along y direction, simulating figure 4.6 the following result is obtained:

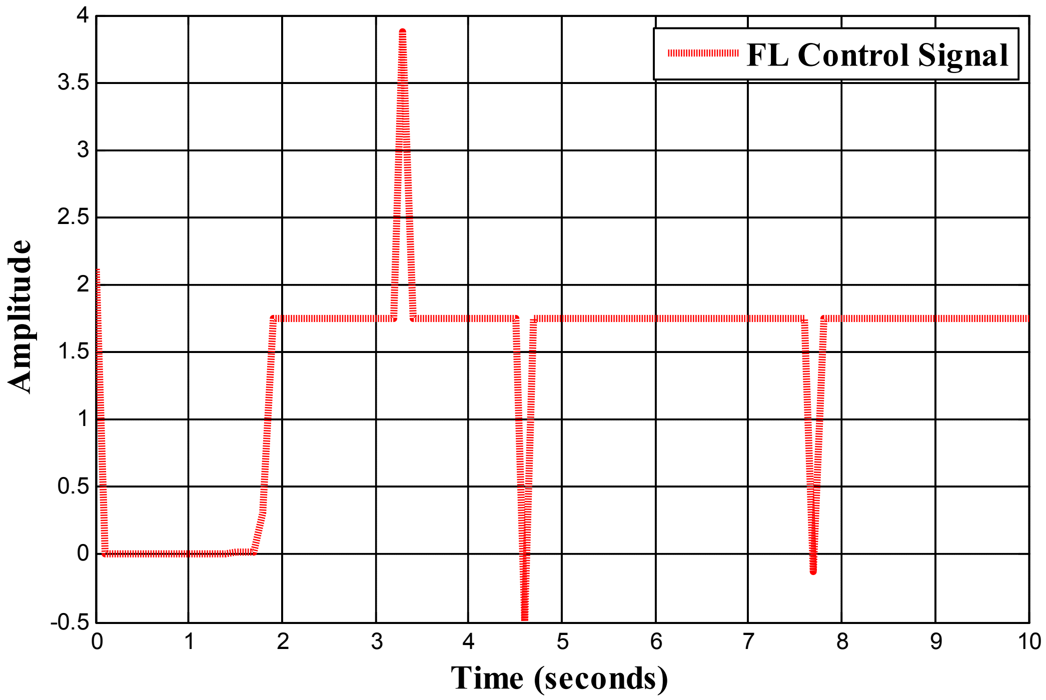

Fig 4.9: Response of control signal for non linear system with FLC

This is the control signal for the position of the robot along y direction and is produced by the output of the FLC which is served as the input signal to the whole robot system. The nature of its response demonstrated that the control signal applied to system non linear configuration model with FLC is very small in magnitude and can easily be realised practically.

In terms of control signal produced by PID controller along x direction, with 10seconds simulation time, figure 4.7 was simulated and the following result was obtained and demonstrated in figure 4.10:

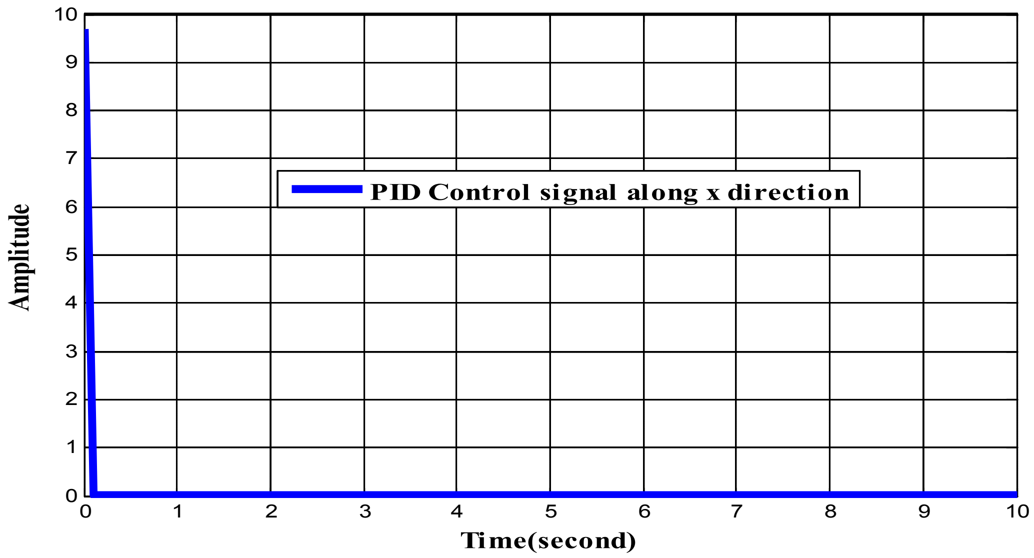

Fig 4.10: Control signal of the robot along x direction with PID

This is the control signal of the robot position along x direction and is produced by PID controller. This control signal is served as the input signal to the robot system.

For the control signal produced by FLC along x direction, figure 4.6 was simulated and the following result was obtained and demonstrated in figure 4.11 as:

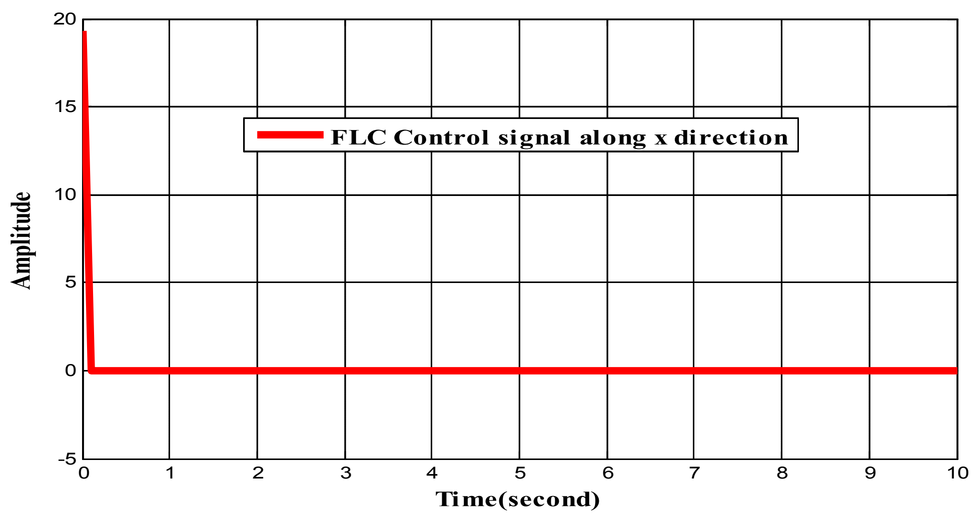

Fig 4.11: Control signal of the robot along x axis with FLC

Similarly, this control signal is produced by the output of the FLC for the position of the robot along x direction and is fed into the robot system as an input signal. The nature of its response shows that the signal can easily be realised practically.

Similarly, for the control signal produced by PID controller in terms of robot position along y direction, figure 4.7 was simulated and the following result was obtained and demonstrated in figure 4.12 as:

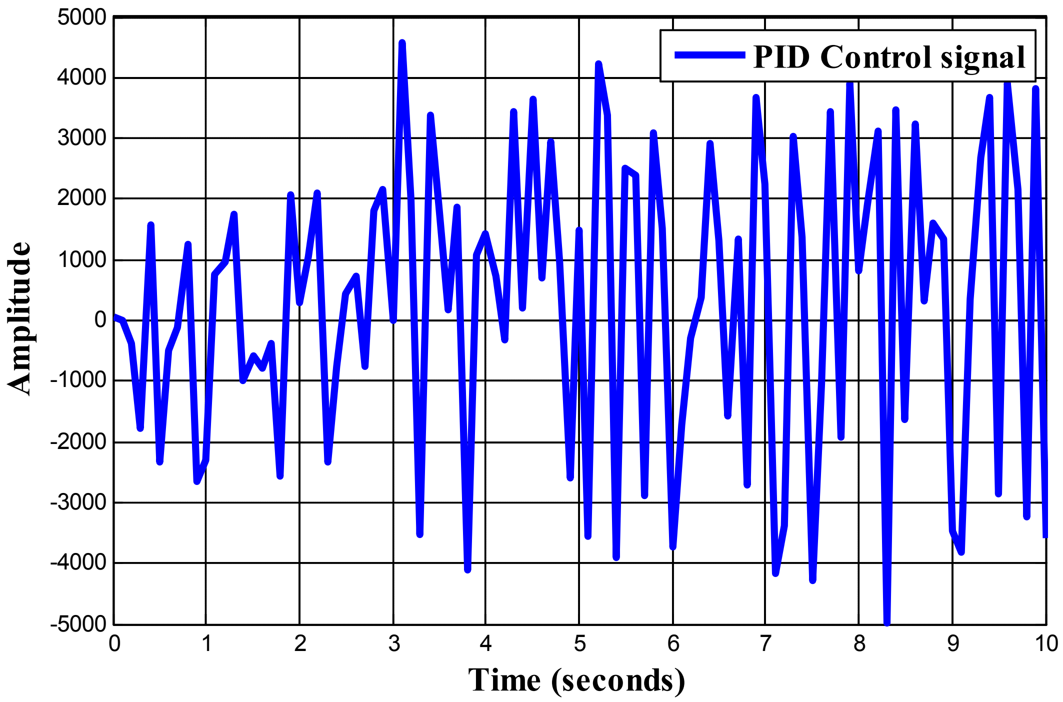

Fig 4.12: Response of control signal for non linear model with PID

This control signal is produced by the output of the PID for the configuration of the robot position along y direction and is served as the input signal to the whole robot system. The nature of its response in terms of magnitude demonstrated that system control signal with PID is shown to be with very high amplitude ranging from a magnitude of -5000 to 5000. In practical implementation, this control signal cannot be easily realised and it must require a gain of high value as compared with that of FLC ranging from a magnitude of -0.5 to 4 of which with a gain of small value, the realisation can be attained.

4.8 Conclusion

In this chapter, the simulations of non linear model with FLC and PID were carried out and the corresponding results were plotted and tabulated. Similarly the simulation of non linear robot model with respect to robot position in terms of x and y axes were also carried out with their corresponding results being plotted and tabulated. Finally the control signals with regards to FLC and PID were plotted and compared for different configurations set up.

CHAPTER FIVE

Conclusion and Recommendation

5.1 Conclusion

In this research, the mathematical model for two wheel mobile robot is obtained using the consideration of the robot been moved from a base frame to a moving frame. In order to address the issue of inverse kinematic problem, the position of the robot in terms of x and y directions are obtained at the simulation configuration stage. Also, the mathematical model of PMDC motor in terms of its dynamic equations are obtained, finally the kinematic robot model alongside PMDC motor model were combined and built together at the simulation stage to produced a complete mobile robot system model.

Having the complete system model at hand, a proposed fuzzy logic controller FLC was developed and incorporated in the system for both position of the robot in terms of x and y directions and non linear kinematic model of the robot system using Mamdani fuzzy inference system. Similarly, proportional integral and differential PID controller was also designed and incorporated in the same system. FLC and PID controllers produced different control signals which fed into the robot system for the purpose of controlling the moving linear velocities and positions along x-y directions.

For the purpose of validation, the performance of the two controllers was tested in the Matlab/Simulink environment using some of the performance indices like settling time, rise time, percentage overshoot and steady state error. The result obtained shows that fuzzy logic controller is a better of the two controllers considered for both position of the robot and nonlinear kinematic models. For example response for fuzzy logic controller under a unit step input has 0.89secods settling time and 0.44seconds rise time respectively while PID controller produced a settling time of 1.68sec, and 0.88seconds rise time respectively, this shows a superiority of FLC, also in terms of robot position along y-axis, the response of FLC has a settling time of 8.53seconds and 1.2seconds rise time respectively, as against the PID controller which produced a settling time of 9.71seconds and 8.06seconds rise time respectively. Comparing the results obtained both from robot linear velocity and position of the robot in terms of x and y directions, with the results of the control signal obtained based on their magnitude, we can therefore conclude that, the proposed fuzzy logic controller could be a valuable and efficient controller for the robot system.

5.2 Contributions

- Modification and development of a combined kinematic robot model with the Permanent Magnet DC Motor (PMDC) as an actuator to get a complete mobile robot model, because of its unique characteristics such as:
    - Its speed can easily be control
    - Its reversible
    - Speed /Torque characteristics can easily be archived
- Each output of the robot system was controlled and investigated with respect to other outputs under the proposed controller, so as to reduce the interaction between the components of the system.
- In order to introduce the inverse kinematic problem, apart from controlling the speed of the robot along x-y directions, the corresponding positions along these directions were also considered, by integrating equation (3.12) in chapter three and modification of simulation configuration set up shown in figure 3.6.

5.3 Recommendations

Having successfully carried out this research, the following research gaps are recommended for further studies:

- Practical implementation of the FLC would provide more insight on the understanding of the controller process
- Development of robot system to avoid obstacle will improve the independency of the robot
- Movement of the robot in a circular path will be a good addition to the functionality of the robot

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