POSITION CONTROL OF GYMNASTIC ROBOT USING FUZZY LOGIC CONTROLLER

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MAY, 2016

DECLARATION

I ADAMU ABBA MUHAMMAD hereby declare that this work is the product of my research efforts undertaken under the supervision of dean faculty of Engineering Professor Ado Dan-Isa 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 ADAMU ABBA MUHAMMAD (SPS/12/MEE/00016) were carried out under my supervision

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DEDICATION

This research work is dedicated to my lovely mother Hajiya Aishatu Muhammad Adamu and my late father Malam Muhammad Adamu Abubakar. (May Allah grant him Aljannah Firdaus)

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ABSTRACT

Position control and stability is very essential in robotic systems and becomes more difficult to achieve for a nonlinear system. Gymnastic robot are used by athletes for body building and also in the medical field for smooth massage of paralyzed patients. This work proposes Fuzzy Logic Control (FLC) schemes and comparing the performance of the proposed controller with a system tuned Proportional-Integra-Derivative (PID) control on Gymnastic Robot used to massage paralyzed patients. The FLC scheme was designed with the joint angle error and its derivative as the input of the controller, the Fuzzy controller provides control signal (force) that keep the angle of the Gymnastic Robot at a desired angular position. Fuzzy logic toolbox of MATLAB/Simulink environment was used in realizing the work. The aim is to put the Gymnastic Robot in a desired position. The results obtained from the proposed controller and the comparative controller were analysed based on rise time, settling time, percentage overshoot and steady state error. Several test output of 0.2, 0.5 and 1.0 radians were tested. FLC proved superiority over the conventional PID controller, for stability concept in terms of time domain specification, FLC settled in 2.8 seconds while conventional PID settled in 1.38 seconds for a test output of 0.2 radians (11.5°) in controlling the angle Theta2. In controlling Theta3, FLC settled in 2.4 seconds and PID settled in 1.35 seconds. FLC has zero steady state error and zero percentage overshoot. Therefore, FLC is considered a better controller in this application. Nonetheless, the two control schemes could be a valuable controller for the system.

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CHAPTER ONE

1.1 Introduction

A robot is a reprogrammable, multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motion for the performance of variety of tasks. (Mustapha 2013).Robot are used for dangerousjobs like cleaning of the main circulating pump housing in the nuclear plant and repetitive jobs that are boring, stressful or labor-intensive for human.

Robot arm is probably the most mathematically complex robot you could ever build because of coupling between links, strict non-linearity and time varying parameters. (Banga and Kaur 2012)

Robot control is very difficult, tracing a desired path in robot manipulator offers many practical and theoretical challenges due to the complexities of the robot dynamics and requirements to achieve high precision trajectory tracing in the cases of high velocity movement and highly varying loads.

The main concern of robotic application is to find an effective controller to achieve accurate tracking of desired motion smoothly. Robot manipulators are nonlinear, dynamically coupled and often of high order, it is not adequate to use linear servo control if accurate performance in high bandwidth operations is desired. Many efforts have been made in developing control scheme to achieve the precise tracking control of robot manipulators.

Conventional control techniques such as PID control, nonlinear feedback control, adaptive control, sliding mode control and LQR control have many advantages. When the values of the control parameters are known, the control signals are generated exactly. Also, when the underlying assumptions are satisfied, many of these provide good stability, robustness to model uncertainties, disturbances and speed of response. However there are several disadvantages. The control algorithms are hard or inflexible and cannot generally handle ‘soft’ intelligent control which may involve reasoning, inference making using incomplete vague, non-crisp, qualitative information, learning, self-organization through past experience and knowledge.

Fuzzy logic control has a great potential since it is able to compensate for the uncertain nonlinear dynamics using the programming capability of human control behavior. The main features of fuzzy control is that a control knowledge base is available within the controller and control actions are generated by applying existing conditions or data to the knowledge base, making use of inference mechanism. Also, the knowledge base and inference mechanism can handle non-crisp and incomplete information.

Fuzzy logic control does not require a conventional model of the process, whereas most conventional techniques require either an analytical model or an experimental model. Fuzzy logic control is particularly suitable for complex and ill-defined process in which analytical modeling is difficult due to the fact that the process is not completely known and experimental model identification is not feasible. This dissertation proposes a fuzzy position control method which is simple and only uses feedback control. An important advantage of proposed position control method is that it works even for trajectory tracking at high speed where Corololis and centrifugal forces cannot be ignored.

1.2 Research Motivation

Gymnastic robot are used to massage paralyzed patients, they need to have a smooth motion. Any vibration caused by oscillation in the system may bring pain to the patient. Real life gymnastic robot systems are nonlinear in nature and therefore the mathematical model for such systems are often difficult to realize. The formulation of mathematical model for such systemsrequires many assumptions which consequently results in an approximate model hence may not capture well the vital features of the system. Therefore designing a controller using PID for such model becomes quite difficult due to tuning of its parameters which is mostly done manually. This work researches the use of Fuzzy logic controller to overcome the problem of such oscillation for a three link gymnastic robot system.

1.3 Statement Of The Problem

Robotic Manipulator have gained much importance in real life. The need for its efficient usage is always a challenging task. Speed, precision and accuracy are important in robotics and these are main factors in solving the problem of delay, error and human risk in hazardous environment.

Robot manipulators represent complex dynamic systems with extremely variable inner parameters as well as the large intensive contact with the environment, an accurate control of such a complex system deals with the problem of uncertainty.

Most of conventional controllers like PID, Linear Quadratic Regulator (LQR) etc. performs well when they are applied to linear system but their performances become poor when they are applied to nonlinear systems because, exact mathematical model for such system is difficult and often not feasible without approximations. In addition conventional controller like PID requires adequate tuning of the gain parameters, this task usually takes time and lot of effort to achieve when it is tuned traditionally. Fuzzy logic controller perform much better than the conventional controllers when they are applied to nonlinear system because mathematical models are not necessary before they can be applied. Gymnastic robot are nonlinear system with much oscillation, there is therefore the need to tackle the problem of oscillation in such robot manipulators to increase its accuracy, speed and precision.

1.4 Aim And Objectives

The aim of this research is to use Fuzzy logic to control the position of a robotic manipulator and will be achieved through the following objectives;

i- Analyzing each inputto the gymnastic robot systemseparately.

ii- Design a Fuzzy Logic Controller (FLC) to control the position of the robot manipulator.

iii- Use system tuned PID controller to control the position of the same robot manipulator.

iv- Compare the control performance of robot manipulator under FLC and PID controllers.

1.5 Research Methodologies

In order to explore the capabilities of fuzzy logic controllers in effectively controlling the position of a three link gymnastic robot and to show their superiority over other conventional control techniques, the robot model (Jian and Zushu 2003) was adopted.Its kinematic equations was based on Dernavit-Hartenberg approach, dynamic equation governing the system was achieved through Lagrange formulation. The fuzzy controller is a “min-max’, “If-

Then" Mamdani controller whose performance will be compared with a system tuned PID controller.

1.6 Scope and Limitation

The scope of this work is to design a Fuzzy logic controller that will control the position of nonlinear gymnastic robot and for a smooth massage of paralyzed patients. However, the design controller is not general for all nonlinear system and may not be applicable to all kind of paralysis cases.

1.7 Report organization

A brief description for each chapter and the organization of this thesis is structured as follows;

Chapter two presents the previous works and discussions by individuals in different areas of robotic manipulators, as well some theoretical background of the controllers used.

Chapter three presents, the dynamic model for the gymnastic robot and the common problem in robotics known as kinematic analysis which includes the forward kinematics and inverse kinematics. Simulink model and Fuzzy logic controller design is also presented in this chapter.

Chapter four shows the simulation and results of Fuzzy position control and PID control scheme for precise tracking of gymnastic robot position.

Chapter five presents the conclusion, contribution of this work and recommendation for future works.

CHAPTER TWO

LITERATURE REVIEW

2.1Introduction

This chapter contains literature review of some previous works on robot manipulators, fuzzy logic controller and PID controllers. It also looks at the theoretical background of the control schemes used in this work.

2.2Related Works

Xgo (2012) presented tracking control for robot manipulator. He used Robust Adaptive Neuro-Fuzzy Network Control (RANFNC) to achieve joint position control of a two-link robot manipulator. In his control scheme, a four-layer Neural-Fuzzy-Network (NFN) is used for the main role, and the adaptive tuning laws of network parameters are derived from Lyapunov stability theorem to ensure network convergence as well as stable control performance.

All the system dynamics could be unknown and no strict constraint to stop control. Simulated results of two link robot manipulator via various existing control like PD controller shows the desired position tracking response of the RANFNC System can be controlled closely following specific reference trajectories under wide range of disturbance.

In the work proposed by Zadeh and Zarif (2014), a Fuzzy compensation is used to compensate uncertainties in a dynamic model of work presented. External disturbance (such as friction) comparisons of the controller with conventional feedback linearization torque controller under uncertainties are carried out. Comparative results demonstrates that the adaptive control scheme is effective in improving control performance in the presence of modeling uncertainties and external force. The convergence and stability of the control scheme is proved by using the Lyapunov method. The stability analysis verifies that the system states will be bounded within a limit. Computer simulation of a three-link SCARA robot manipulator is carried out and the result shows that the control approach is robust with a very good tracking performance.

Banga and Kaur (2012), carried out a work on the simulation of robotic manipulator having three links. An optimal movement of three-DoF robotic arm using inverse kinematics was presented. The paper reports an optimization method based on genetic algorithmwhich is developed in order to obtain the optimal angular displacement of the robotic arm. Results obtained prove that the proposed method has some set back in tracking the angle effectively due to dynamic uncertainties.

Yazdenzad et al (2014) proposed Robust Integral of the Sign of the Error (RISE) feedback Control Scheme in a three degree – of – freedom (DoF) robot manipulator tracking problem. This method compensates for nonlinear disturbances and uncertainties in the dynamic model, and results in asymptotic trajectory tracking. To avoid selecting the parameters of the RISE controller by time-consuming trial and error method, Particle Swarm Optimization (PSO) algorithm is employed as an intelligent method of selecting the parameters. The objective of the PSO algorithm is to find the set of parameters that minimizes the root mean squared error as its fitness function. The proposed method attains tracking goal, without any chattering in control input.

The conclusion drawn in this paper was the proposed control compensates for uncertainties and bounded external disturbances without any chattering in control input and simulations result have demonstrated the effectiveness of the proposed controller with its ability to provide an asymptotic tracking performance.

Faiz and Abbas (2013) designed and implemented two types of control strategy, PID Controller and fuzzy like PD Controller to control Selective Compliance Assembly Robotic Arm (SCARA) with 4 – DoF to a desired position with specific orientation.

Conclusion drawn from their work shows that the response of the robotic arm using PID Controller is fast with zero steady stateerror but contains overshoot before settling and for the fuzzy like PD Controller, the response is smooth and fast like PID Controller.

The work presented byNigam and Alvandra (2008) on Quantitative Feedback Theory (QFT) for single and two link SCARA robot designed to achieve desired position control that requires domain specifications. Their work aims at showing the drawback of some controllers (like PID) which cannot change automatically if the system parameter changes.

The simulation results presented shows that QFT gives the required response with parametric uncertainty of the system when compared with conventional control methods.

Patel (2013) presented a work on how to measure the performance of a robot manipulator using its dynamics, the work presented aims at reducing the level of dynamic uncertainties in robot manipulator systems using Adaptive Neuro Fuzzy Inference Strategy (ANFIS). He used a case study of two degree of freedom (2 DoF) SCARA.

Results shows successful mathematical modeling of the SCARA and its simulink. Conclusion drawn shows that ANFIS is effective and works well with linear, optimization and adaptive techniques. It also shows that this control strategy is faster than other conventional (like PID control) control strategies. It was also shown that the use of photoelectric sensor as sensing element in the control system increases its effectiveness.

In 2014, a work was carried outon motion planning for a 3-DOF SCARA robot using Fuzzy controller was presented. The author Jaiswal demonstrated that a free trajectory exist between any two configuration in a connected component of the free space for the 3-DOF.

The presented motion planner minimizes number of times the robot velocity must come to zero, increases its productivity and fast trajectory tracking with time according to the manipulator dynamics.

In1992, Wang and Mendel added some of the potential benefits of using fuzzy logic controllers to control robot manipulator systems. They presented the development of a fuzzy logic controller using a four (4) input Takag – Sugeno fuzzy model. The main idea of their work is to implement and optimize fuzzy logic control algorithms in order to make robot manipulators to be set to a desired position and at the same time reducing the computational time of the controller. The achieved result of their work showed that the proposed fuzzy logic controller is more robust to parameter variations when compared with PID Controller.

2.3 Theoretical Background

Brief theories on relevant control schemes used in this work are considered in the following subsection. This will explain some underlying principles regarding these control schemes.

2.3.1Proportional-plus-Integral-plus-Derivative Controller (PID)

This is the combination of proportional, integral and derivative control action and it is sometimes referred to as three action controller because it consist of three element:

proportional (P), integral (I) and derivative action. There are a number of controllers based upon the three term PID controller; the most common are the P or PI type, which together account for the majority of industrial control elements.**(Saeed 2007)**

The PID control block diagram below shows the feedback flow on which the PID controller operates. An input e(t) is send to the controller and the control output from the control will be send to the system for control there by giving an output m(t) which is controlled.

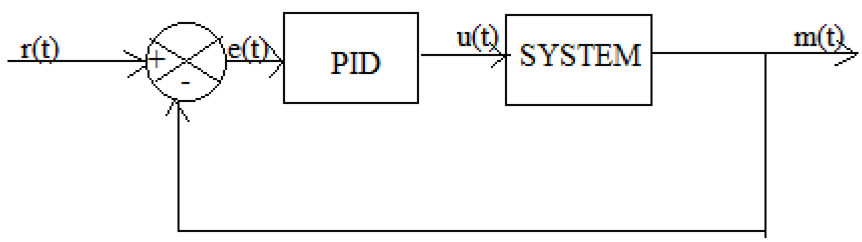


Figure 2.1 PID control block diagram

$$m(t) = K_p e(t) + K_p \frac{1}{T_i}\int_0^t e(t)dt + K_p T_d \frac{d}{dt} e(t) \tag{2.1}$$

Where: K_p = proportional channel gain

T_d = derivative time constant

T_i = integral time constant.

e(t) =input variable

u(t) = control signal

m(t) = system output

In Laplace form

$$M(s) = K_p E(s) + \frac{K_p}{sT_i} E(s) + K_p T_d sE(s) \tag{2.2}$$

The transfer function is given by:

$$\frac{M(s)}{E(s)} = K_p(1 + \frac{1}{sT_i} + sT_d) \quad (2.3)$$

2.3.2 Fuzzy Logic Control (FLC)

Fuzzy Logic was introduced in 1965 by Lotfi A. Zadeh. Basically, Fuzzy Logic (FL) is a multi-value logic that defines intermediate valuesbetween traditional evaluations like true/false, yes/no, high/low, etcetera. These intermediate values can be formulated mathematically andprocessed by computers, in order to apply a more human like way ofthinking.**(Summathi and Paneersalian 2010).** The first industrial applications were made in 1970s. Ibrahim Mamdani used Fuzzy logic to control a steam power plant that he could not get under control. After this, the growth in the application of fuzzy logic had witnessed a tremendous increase due to its flexibility and robustness in the area of control, consumer products, data processing, fault diagnosis, man machine interfacing and decision support systems.**(Summathi and Paneersalian 2010).**

2.3.2.1Fuzzy Set and Membership Function

In conventional mathematics, the concept of set is very simple and clear. A set is define as the collection of similar data. Objects either belong to a given set or they don't (i.e. bivalent). In classical set theory $\mu_A(x)$ has only values 0 ("false") and 1 ("true"),so there are two values of truth. Such sets are also called *crisp sets*. This set has some draw back when applying to a real life situation. For instance, in classifying a set of people based on their skin complexion, it can only be done into either light or dark in complexion using the above concept. The degree of the complexion here cannot be represented since it is a two value set. However, fuzzy set does not face the above limitation as it is multi value. A Fuzzy set (non-crisp set) can be defined as a set to which objects can belong to different degrees, called *grades of membership.* In a

Fuzzy set all the elements that belong to the set are named and are assigned a number between 0 and 1. This number demonstrates the degree to which this element belongs to the defined Fuzzy set. We thus add to every element a number, which constitutes the membership degree of this element. Actually, a Fuzzy set is given by its membership function, the value of which determines whether the element belongs to a fuzzy set and to what degree. Membership function can be piecewise linear functions (triangular and trapezoidal), quadratic, Gaussian. The linear function is more widely used because they are mathematically simpler to implement and no appreciable performance improvement has been recorded when more complex function are used **(Chen et al 2004).** For illustration purposes, Figure 2.1 shows triangular membership function, the y-axis illustrate to what degree a linguistic variable belong and the x-axis is the universe of discourse.

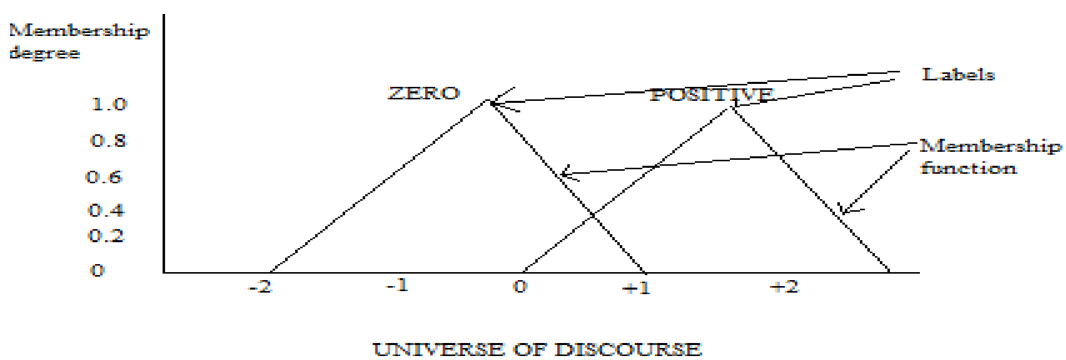


Figure 2.2Fuzzy Membership function

2.3.2.2 Fuzzy Linguistic Variable

Linguistic variablesare variables with values that are words or sentences from natural language. For example, referring to the set of tall people, *tall* is a linguistic variable. Sensory inputs are linguistic variables, or nouns in a natural language, for example, temperature-pressure, displacement, etc.**(Summathi and Paneersalian 2010).**Linguistic variables can have possible numerical values that quantity of interest can assume (certain level of universe of discourse). In this work, one of the input to Fuzzy controller is the *angle error* (θ). Angle error is thus a linguistic variable and quantity of interest can assume certain level of universe of discourse. We can also use the fuzzy variable membership functions of *Negative-error*, and *Positive-error* to qualify the linguistic variable *angle error.* Hedges are used to further qualify the linguistic variables. In this case the error may be categorized as positive, positive-large or big-positive; the terms large and big are the hedges.

2.4.3 Fuzzy Controller Operation

The operation of a Fuzzy controller is illustrated in Figure 2.3. It shows the processes needed to be taken in order to achieve fuzzy control action.

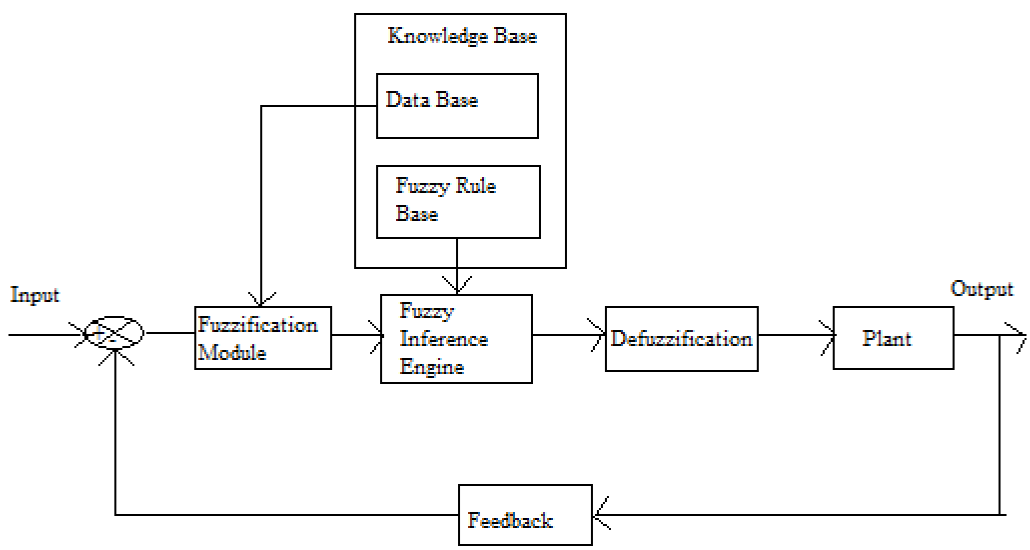


Figure 2.3 Fuzzy control system block diagram

To achieve fuzzy control, the following steps should be followed:

Fuzzification Stage: In this stage, input values are mapped to domain of fuzzy variable (i.e. the crisp input variables are assigned linguistic label). In this work, symmetrical triangular membership functions are used. Then the fuzzy rule base must be formed based on the expert knowledge of the system. For example, if *angle error (e) is negative big(NB) and the derivative angle error(e) is negative big(NB) then Force (F) is positive big(PB)*. This is one of many possible fuzzy rules that can be used to achieve fuzzy control of a given system. These fuzzy rules are then applied on fuzzy input variables to give fuzzy output variables. This process is called fuzzy inference stage.

Fuzzy inference engine: There are two types of approach to follow: Composition based inference and Individual rule-based inference approach. The former which make use MAX-MIN is used in this work as an inference engine to determine the degree of membership function of the output variables. MAX-MIN was used to have a wider range of control considering all values for control. **(Wang and Mendel 1992)**

Defuzzification Stage: In this stage, all the fuzzy sets are aggregated to obtain a crisp output. In fact, it's aimed at producing a non-fuzzy control that best represent the degree of certainty of an inferred fuzzy control action. There are several numbers of procedures of defuzzifying the rules output-aggregate for the Mamdani method. The procedures such as Center of gravity, First of maxima, Middle of maxima, Center of sum etcetera. In this work Center of gravity was used because it is considered as the most efficient in that it gives a defuzzification output which conveys the real meaning of the action that had to be taken at that instance.

The efficiency of the Fuzzy controller and the comparator controller (i.e. the PID controller) in this thesis will be tested based on settling time, rise time, steady state error and percentage overshoot which are typical performance measures used often in the literature.

2.4Performance Measures

These are some standard criteria used to explain the behavior of system response curves. These include:

Settling Time (t_s)

Settling time is defined as the time for the response to reach, and stay within the specified range (2% to 5%) of its final value. This is mathematically presented in (2.4)

$$t_s = \frac{4}{\xi\omega_n} \quad (2.4)$$

Rise Time (t_r)

The time required for the waveform to go from 0.1 of the final value to 0.9 of the final value for over damped systems and 0 to 1 for underdamped system. This is given by (2.5)

$$t_r = \frac{\pi - \tan^{-1}\left(\frac{\sqrt{1-\xi^2}}{\xi}\right)}{\omega_n\sqrt{1-\xi^2}} \quad (2.5)$$

Overshoot (M_p)

This is the amount that the waveform overshoots (rises above) the steady-state, or final value at the peak time. Mathematically expressed in (2.6)

$$M_p = e^{-\frac{\pi\xi}{\sqrt{1-\xi^2}}} \quad (2.6)$$

Where:

ξ= damping factor

ω_n= natural frequency of oscillation

Steady State Error (e_{ss})

This is the difference between the input and the output for a prescribed test input as time tends to infinity. Mathematically presented in (2.7)

$$e_{ss} = \lim_{t\to\infty}\left[r(t) - c(t) \right] \tag{2.7}$$

Where:

$r(t)$ = reference input

$c(t)$ = actual output

In conclusion, review of some works related to the control scheme were discussed. The theoretical background of controllers used were seen and the performance measures used to testify the efficiency of both controllers were presented.

CHAPTER THREE

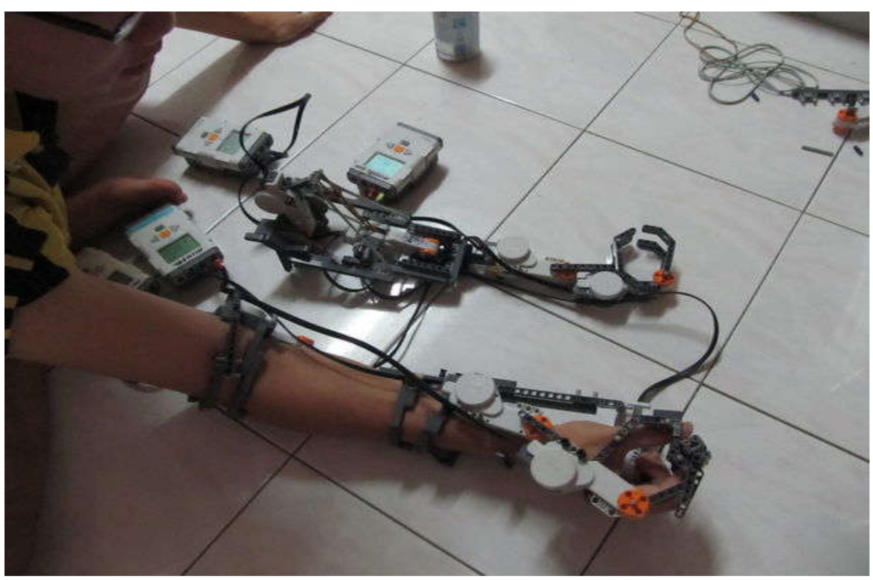
MATERIALS AND METHOD

3.1Introduction

In this chapter, the adopted robotic manipulator is shown, the generalized forces driving the arm are calculated with regards to the external force attached to the robot manipulator. The design control is based on “IF-THEN” “MIN-MAX” Mamdani principle. It is a two input (error and derivative-error) and single output controller.

3.2Gymnastic Robot Model

Gymnastic robot are used in medical field for smooth massage of paralyzed patient. Patient suffering from paralysis find it difficult to move the paralyzed part of the body so an external massage is often done to the paralyzed part of the body which will help the patient to regain his/her conscious. Platebelow shows a Gymnastic robot used to massage the hand of a paralyzed patient.



Gymnastic robot used in this work is a three (3) link robot arm with two movable joints (rotational joints) which can move independently. The two movable joints of the gymnastic robot can be positioned using a DC motor (mc_1 and $mc_2$with inputs U_1 and U_2 respectively). Position of this manipulatorcan be set to a variable angle Θ_2 and $\Theta_3$using mc_1 and mc_2respectively.

Fig 3.1is a schematic diagram of a three (3) links gymnastic bar robot manipulator showing its link parameters.

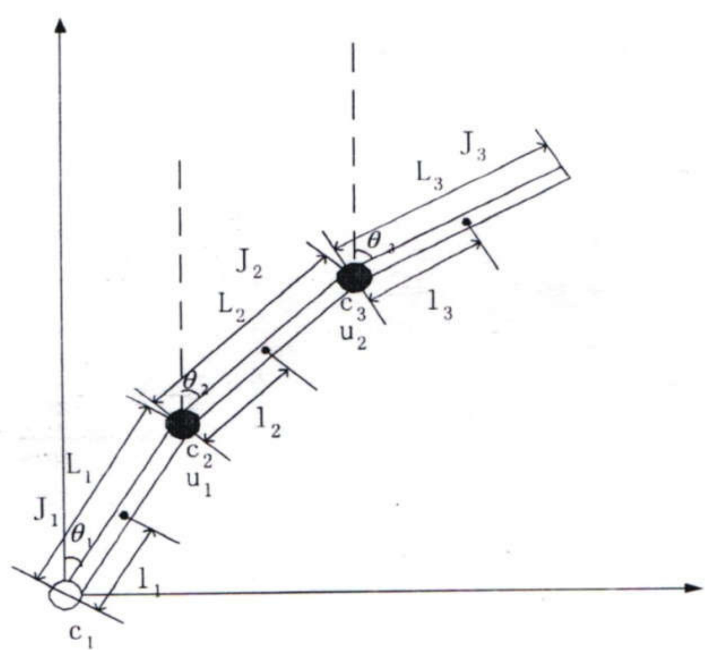


Figure 3.1 Three Link Gymnastic Robot

From the gymnastic robot diagram, the parameters related to the system are defined in table (3.1)

Table 3.1 Parameter Table of Gymnastic Robot

S/No.	Symbol	Representation
1.	θ_i	Displacement angle of i-th joint
2.	m_i	Mass of i-th link
3.	J_i	Inertia ofi-th link about an axis through the center of mass and parallel to z.
4.	L_i	i-th link length
5.	l_i	Distance between joint i and the center of mass of i-th link.

3.3Robot Equation

Robot model are associated with equations which define the position and orientation of the robot (kinematic equation) and equation defining its generalized forces related to each link and the whole system (dynamic equation).

3.3.1 Kinematic Equation

The kinematics of a robotic manipulator refer to the mathematical equations that describe the forward and inverse relationships between the joint variables (angular positions of the joints) and the Cartesian position coordinates of the manipulator. (Nigam and Alvandra 2008)

In this work, robot manipulator kinematic equation is derived using Dernavit-Hartenberg (DH) approach, this approach is simple and direct. Equation of each link is derived individually then the system homogenous transformation matrix is computed.

Table below defines the parameters associated with DH approach in computing the robot manipulator kinematic equation.

Table 3.2 DH Table

Link (i)	**Joint Angle (θ_i)**	**Link Twist (α_i)**	**Link length (a_i)**	**Link offset (d_i)**
1	θ_1	0	L_1	0
2	θ_2	0	L_2	0
3	θ_3	0	L_3	0

Where table 3.2 shows the parameters related to Fig 3.1 defined below;

Joint angle (θ_i) = angle from the axis X_{i-1} to the axis X_i about the axis Z_{i-1}.

Link offset (d_i): = perpendicular distance from the origin O_{i-1} to the intersection point of the axis X_i with the axis along the axis Z_{i-1}.

Link twist angle (α_i): = angle from the axis Z_{i-1} to the axis Z_i measured about the axis X_i.

Link length (a_i): = distance from the axis Z_{i-1} to the axis Z_i measured along the axis X_i.

Equation 3.1, 3.2 and 3.3 shows base to i-th link are respectively.

Where

i = 0, 1, 2……

-Base to link1

$$ {}^{0}T_{1} = \begin{matrix} C_1 & S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \qquad (3.1) $$

Where,

$C_1 = \cos\Theta_1$

$S_1 = \sin\Theta_1$

Link1 to link2

$$ {}^{1}T_{2} = \begin{matrix} C_{12} & S_{12} & 0 & 0 \\ S_{12} & C_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \quad (3.2) $$

Where,

$C_{12} = \cos(\Theta_{1+}\Theta_2)$

$S_{12} = \sin(\Theta_{1+}\Theta_2)$

Link2 to link3

$$ {}^{2}T_{3} = \begin{matrix} C_{23} & S_{23} & 0 & 0 \\ S_{23} & C_{23} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \quad (3.3) $$

Where,

$C_{12} = \cos(\Theta_{2+}\Theta_3)$

$S_{12} = \sin(\Theta_{2+}\Theta_3)$

Hence homogenous transformation matrix is given by (3.4) below,

$$ {}^{0}T_{3} = \begin{matrix} C_{123} & S_{123} & 0 & r_1 \\ S_{123} & C_{123} & 0 & r_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \quad (3.4) $$

Where $C_{123} = \text{Cos}(\theta_1 + \theta_2 + \theta_3)$

$S_{123} = \text{Sin}(\theta_1 + \theta_2 + \theta_3)$

$r_1 = L_1C_1 + L_2C_{12} + L_3 C_{123}$

$r_2 = L_1S_1 + L_2S_{12} + L_3S_{123}$

L_i =Length i_{th} of link

Inverse kinematic of the robot arm is derived using equation (3.5)

$$T_{end-effector}^{base} = T_1^0 T_2^1 T_3^2 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} (3.5)$$

Where r_{ij} is the rotational matrix and p is the translational matrix. Here no translational motion is represented.

3.3.2Robot Dynamic Equation

The dynamic equation of the robot manipulator was derived using Lagrange approach**(Jian and Zushu 2003)** and is given by equation (3.6) below;

$$C = A(\Theta)\Theta + B(\Theta, \Theta)\Theta + D(\Theta)(3.6)$$

Where $A(\Theta)$ = system matrix

$B(\Theta, \Theta)$ = Christofel and corololis symbol

$D(\Theta)$ = disturbance such as friction to the system

C = torque into the system.

Where,

$$A(\theta) = \begin{bmatrix} A_{11} & A_{12}\cos(\theta_2 \quad \theta_1) & A_{13}\cos(\theta_3 \quad \theta_1) \\ A_{12}\cos(\theta_2 \quad \theta_1) & A_{22} & A_{23}\cos(\theta_3 \quad \theta_2) \\ A_{13}\cos(\theta_3 \quad \theta_1) & A_{23}\cos(\theta_3 \quad \theta_2) & A_{33} \end{bmatrix}$$

$$D(\theta) = \begin{bmatrix} D_1 sin\theta_1 \\ D_2 sin\theta_2 \\ D_3 sin\theta_3 \end{bmatrix}$$

$$B(\theta, \theta) = \begin{bmatrix} B_{11} & B_{21}\sin(\theta_2 \quad \theta_1)\theta_2 & B_{13}\sin(\theta_3 \quad \theta_1)\theta_3 \\ B_{21}\sin(\theta_2 \quad \theta_1)\theta_1 & B_{22} & B_{23}\sin(\theta_3 \quad \theta_2)\theta_3 \\ B_{13}\sin(\theta_3 \quad \theta_1)\theta_1 & B_{32}\sin(\theta_3 \quad \theta_2)\theta_2 & B_{33} \end{bmatrix}$$

$$C = \begin{bmatrix} u_1 \\ u_1 \quad u_2 \\ u_2 \end{bmatrix}$$

And A_i, B_i, C_i are constants related to the model physical parameters:

$$A_{11} = m_1 {l_1}^2 + J_1 + (m_2 + m_3 + mc_1 + mc_2){L_1}^2$$

$$A_{12} = (m_2 l_2 \quad + (m_3 + mc_2)L_2)L_1$$

$$A_{13} = m_3 l_3 \quad L_1$$

$$A_{22} = m_2 {l_2}^2 + J_2 + (m_3 + mc_2){L_2}^2$$

$$A_{23} = m_3 l_3 \quad L_2$$

$$A_{33} = m_3 {l_3}^2 + J_3$$

$$B_{11} = \quad (D_1 + D_2)$$

$$B_{12} = D_2 + (m_2 l_2 + (m_3 + mc_2)L_2 \quad)L_1$$

$$B_{13} = m_3 l_3 \quad L_1$$

$$B_{21} = D_2 \quad (m_2 l_2 + (m_3 + mc_2)L_2 \quad)L_1$$

$$B_{22} = \quad (D_2 + D_3)$$

$$B_{23} = D_3 \ + m_3 l_3 \quad L_2$$

$$B_{32} = D_3 \quad m_3 l_3 \quad L_2$$

$$B_{33} = \quad D_3$$

$$D_1 = (m_1 l_1 + (m_2 + m_3 + mc_2)L_1 \quad) g$$

$$D_2 = (m_2 l_2 + (m_3 + mc_2)L_1 \quad) g$$

$$D_3 = m_3 l_3 \quad g$$

Table 3.3 shows the parameters of gymnastic robot used in the simulation of this work, it shows the values related to the links of the robot arm. **(Jian and Zushu 2003).**

Table 3.3 Gymnastic Robot Parameters Table

Variable	Value	Unit		Variable	Value	Unit
L_1	0.25	M		J_1	0.00097395	Kgm^2
L_2	0.25	M		J_2	0.01145800	Kgm^2
L_3	0.50	M		J_3	0.04583300	Kgm^2
l_1	0.125	M		C_1	0.70560	Nms
l_2	0.125	M		C_2	0.70560	Nms
l_3	0.250	M		C_3	0.70560	Nms
m_1	1.87	Kg		mc_1	0.2	Kg
m_2	2.2	Kg		mc_2	0.3	Kg
m_3	2.2	Kg				

3.4Single Link Analysis

Gymnastic robot is a Multi Input Multi Output (MIMO) system with strong coupling between its links, hence controlling the system will be very difficult and with high level of error and damping. As such each the system is decomposed and each link is analyzed separately. In controlling the link angle Θ_2, we consider the input to the first motor mc1 and its corresponding output as active, all other input are zero and the corresponding output angles are at reference (consider zero reference point). Hence, the system is seen as a Single Input Single Output (SISO) system for easier control (mass of inactive motor is added to mass of the link attached).

Similar approach is taken in positioning Θ_3, with input to link three (3) and its corresponding output as active, all other input are inactive and their corresponding angular position at reference (zero angular displacement). Every angle that is at reference, its angular velocity is zero with change in angular velocity as zero (zero angular acceleration)

3.4.1First Link Active

In this subsection, we will consider the first motor (mc1) with input U1 directly attached to link 2 as active with Θ_2 as its corresponding output, the dynamic equation of the system presented in equation (3.6) can be given by below matrix.

$$A(\theta) = \begin{bmatrix} A_{11} & A_{12}\cos\theta_2 & A_{13}\cos\ 0 \\ A_{12}\cos\ \theta_2 & A_{22} & A_{23}\cos\ \theta_2 \\ A_{13}\cos\ 0 & A_{22}\cos\theta_2 & A_{33} \end{bmatrix}$$

$$D(\theta) = \begin{bmatrix} 0 \\ D_2 sin\theta_2 \\ 0 \end{bmatrix}$$

$$B(\theta, \theta) = \begin{bmatrix} B_{11} & B_{21}\sin\ (\theta_2)\theta_2 & 0 \\ 0 & B_{22} & 0 \\ 0 & B_{32}\sin\ (\ \theta_2)\theta_2 & B_{33} \end{bmatrix}$$

$$C = \begin{bmatrix} u_1 \\ u_1 \\ 0 \end{bmatrix}$$

The above matrix represent the system when only link 2 is active. This has reduced the complexity of the system for easier control.

3.4.2Second Link Active

Here, link 2 is considered as inactive therefore, corresponding output is zero. The motor (mc2) with input U2 is active making its corresponding output (Θ_3) active hence, the dynamic equation can be presented below.

$$A(\theta) = \begin{bmatrix} A_{11} & A_{12}\cos\ 0 & A_{13}\cos\ \theta_3 \\ A_{12}\cos\ 0 & A_{22} & A_{23}\cos\ \theta_3 \\ A_{13}\cos\ \theta_3 & A_{23}\cos\ \theta_3 & A_{33} \end{bmatrix}$$

$$D(\theta) = \begin{bmatrix} 0 \\ 0 \\ D_3 sin\theta_3 \end{bmatrix}$$

$$B(\theta, \theta) = \begin{bmatrix} B_{11} & 0 & B_{13}\sin(\theta_3)\theta_3 \\ B_{21}\sin(\theta_2 \quad \theta_1)\theta_1 & B_{22} & B_{23}\sin(\theta_3)\theta_3 \\ 0 & 0 & B_{33} \end{bmatrix}$$

$$C = \begin{bmatrix} u_1 \\ u_1 \quad u_2 \\ u_2 \end{bmatrix}$$

3.5Simulink Model of Gymnastic Robot

Gymnastic robot consist of a subsystems shown in figure (3.2) attached to the robot simulink model shown in figure (3.3).

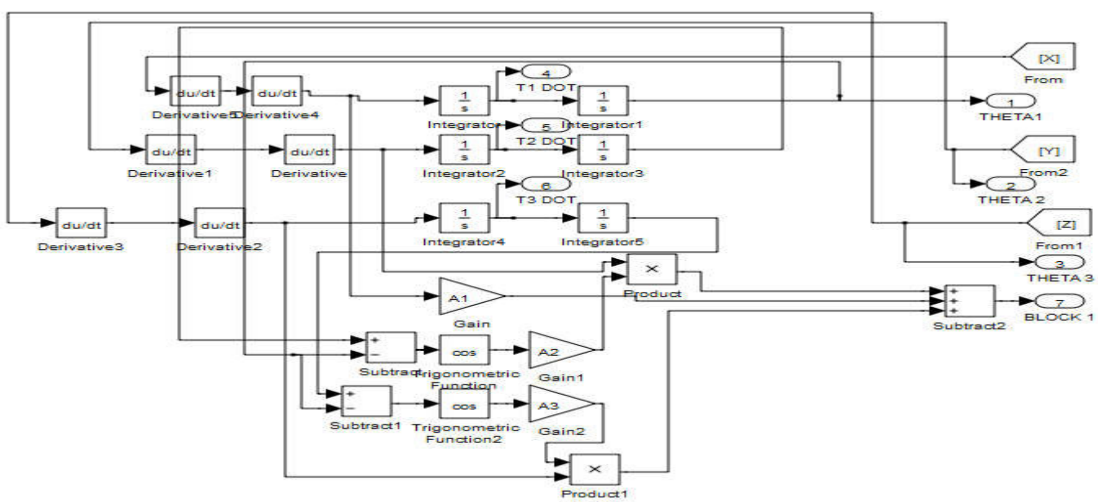


Figure 3.2Simulink Model of Gymnastic Robot Subsystem

Fig 3.2 is a subsystem attached to the general system shown in Fig 3.3, it can be used in subsystem, subsystem1 and subsystem in Fig 3.2 with respect to related value of interest. Considering link 2 as the value of interest, all other parameters of the gymnastic robot other than that of link 2 are considered as zero, therefore, value in Fig 3.2 are set with respect to link 2 alone. The same procedure will be applied when link 3 is active making all other parameters other than that of link 3 as zero.

Fig 3.3 below shows the general simulink model of the system derived in equation 3.3. This relate all parameters of the system when all inputs and links are active. The of this work can be achieved by putting some value related to the model as zero leaving the value of interest as active which reduces the complexity of the system.

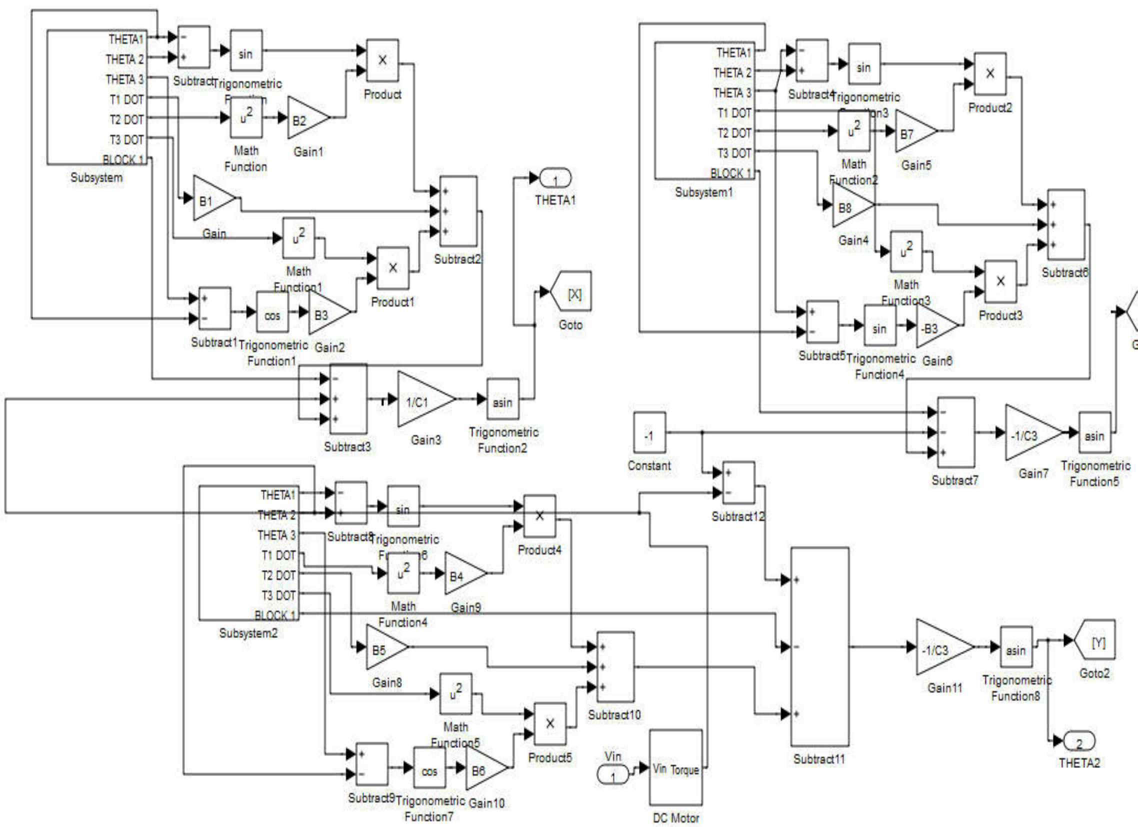


Figure 3.3 Simulink Model of Gymnastic Robot

3.6Controller Design

This section will look into the controllers used and the design approach.

3.6.1 PID Controller Design

In this section, design procedure of the PID based controller is presented. The PID Controller is incorporated in the system as shown in Figure (3.4). The general transfer function of the controller is given as: $C = K_p\left(1 + \frac{1}{sT_i} + sT_d\right)$; $C = K_p + \frac{K_i}{s} + K_d s$

Where: K_p, K_d, and K_i are the controller gains.

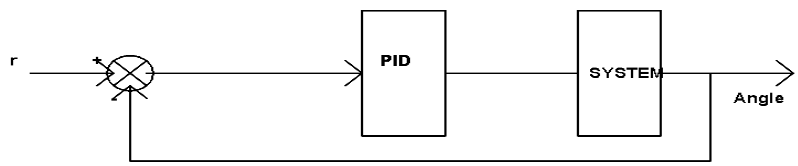


Figure 3.4 PID controller block diagram

Fig 3.4 shows a PID controller block diagram setup, an input r(t) is sent to the system as an error e(t) is fed to the PID controller which will produce a control signal into the system for control. The overall output of the system which is an angle is sent back to the system for next control action.

3.6.2 Fuzzy Logic Controller Design

Classical control theory is based upon a mathematical model of the plant to be controlled. In the robot manipulator adopted **(Jian and Zushu, 2002),** a number of assumptions were made to arrive at the model. In real systems the incomplete model representation may come into play and the performance of the system may deteriorate. Fuzzy controllers have proved capable of excellent performance in situations where the plant model is approximate or even completely unknown. Fuzzy controllers are robust; changes in system parameters do not prevent them from performing adequately.**(Sumathi and Paneerselian, 2010)**

The design of Fuzzy position controller for the gymnastic robot is hereby presented. The following procedures are followed in realizing the fuzzy design using the MATLAB's fuzzy and Simulink toolboxes. The MatLab fuzzy toolbox is used to design the fuzzy inference system (FIS), using the triangular membership functions. In designing this fuzzy controller, there is need to have the angle of the robot manipulator as a measured output quantity, the set-angle (sa) is the required manipulator angle which is also the reference input. The angle error is given as the difference between set-angle and the actual arm angle. It is the difference between the voltage representing the set angle and the actual-angle (aa). In the thesis the angle error and error rate (derivative) are the controller inputs. Angle error is given by:

$$\text{Angle error}(e) = \text{set angle}(sa) - \text{actual angle}(aa) \quad (3.7)$$

Where set-angle (sa) is the reference angle or directed angle i.e. the angle, which the robot arm is directed to attain. The actual-angle (aa) is the actual angle of the arm, which may be less than, equal to or even more than the set-angle depending on the current dynamics of the system. The error might be negative or positive. A positive angle error indicates that the actual arm angle is less than the set-angle in this situation the control signal (force) needs to be increased, since the force will increase the angle of the arm.

This implies that, the angle error is the first variable for the fuzzy controller and is thus the first linguistic variable. Seven membership functions were chosen to represent the domain of angle error. These are:

NEGATIVE BIG (NB)

NEGATIVE MEDIUM (NM)

NEGATIVE SMALL (NS)

ZERO ERROR (ZE)

POSITIVE SMALL (PS)

POSITIVE MEDIUM (PM)

POSITIVE BIG (PB)

These are represented in the Figure 3.5 and they are used to implement the first stage of fuzzy control, that is, the Fuzzification for the angle-error linguistic variable. Figure 3.14 shows the actual membership functions for angle-error as entered in the fuzzy inference system (FIS). The details for designing the FIS are available in the MatLab documentation for the fuzzy control toolbox [16]. Any crisp angle-error is mapped into a fuzzy set by membership functions.

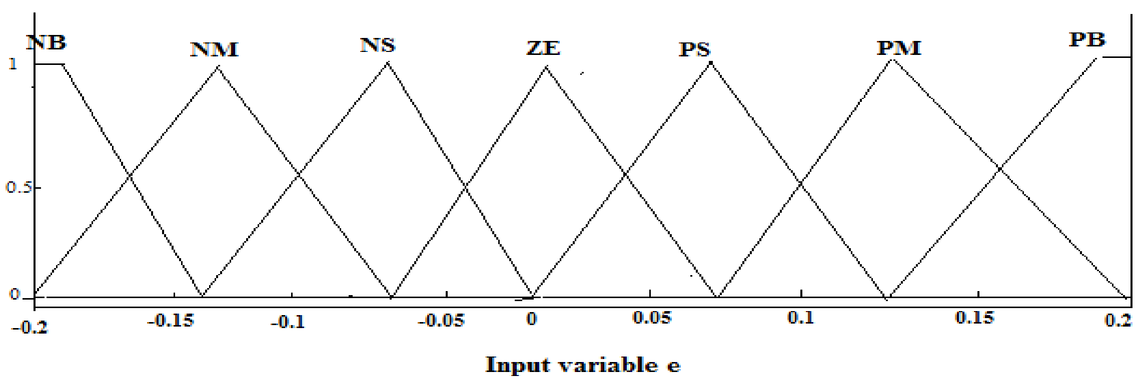


Figure 3.5 Angle-error membership functions

The next input to the fuzzy controller is the linguistic variable, rate of change of error or error-rate, which is practically implemented as the derivative of error. If error is given as e(t), error-rate er(t), set-angle as sa(t) and actual angle as aa(t), where t is time. Therefore, the following relationship holds:

$$er(t) = e(t) - e(t-1) \qquad (3.8)$$

But, $e(t) = sa(t)-aa(t)$,

And $e(t-1) = sa(t) - aa(t-1)$

Sa(t-1)=sa(t), since set angle is constant

Therefore,

$$er(t) = e(t) - e(t-1) = [sa(t)-aa(t)]-[sa(t)-aa(t-1)] \quad (3.9)$$

$$er(t) = aa(t-1) - aa(t) \quad (3.10)$$

This implies that a positive value for er(t) shows that the robot arm angle is decreasing, that is the angle is going back to the reference, and a negative value indicates that the angle is going away from the set reference. The derivative of error was also given seven membership functions for the Fuzzification process just as in the case of error-angle. The input error rate membership functions is shown in Figure 3.6

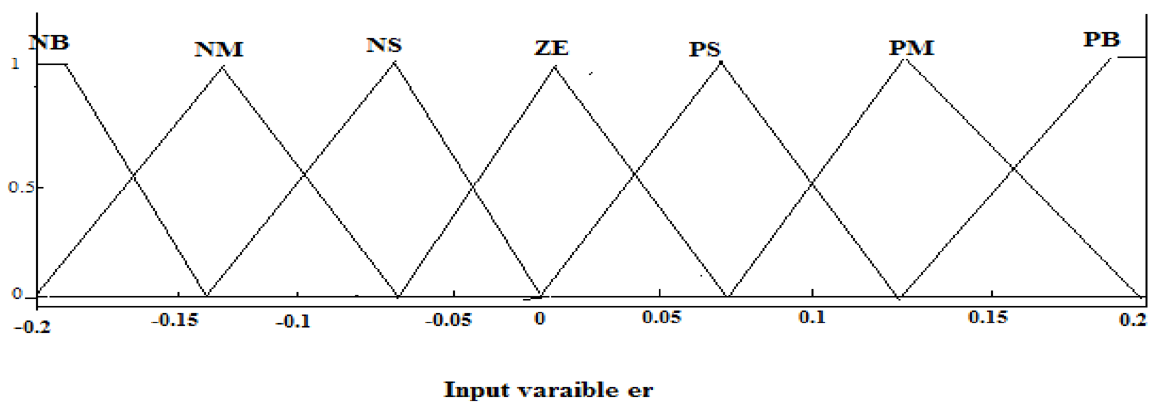


Figure3.6 Angle-error-rate membership functions

From Fig 3.5 and 3.6, -0.2 to 0.2 are selected as the range of membership function for angle error and angle error rate because of the need to track smaller level of input. There is only one output variable from fuzzy inference system and therefore there is only one output linguistic variable as the control force. Seven membership functions were also used for the output variable. This is because controller with much membership function (linguistic variables) would be able to bring the robot manipulator to a target angle very quickly with negligible overshoot as compared with controller with fewer linguistic variables. When determining the number of linguistic variable to use (quantization level), the designer must keep the application in mind. Note that, controller implemented with few linguistic variables would not only save development time, but the resulting control software will be able to run on less sophisticated (and thus less expensive) hardware [13]. The membership function is shown in Figure 3.16.

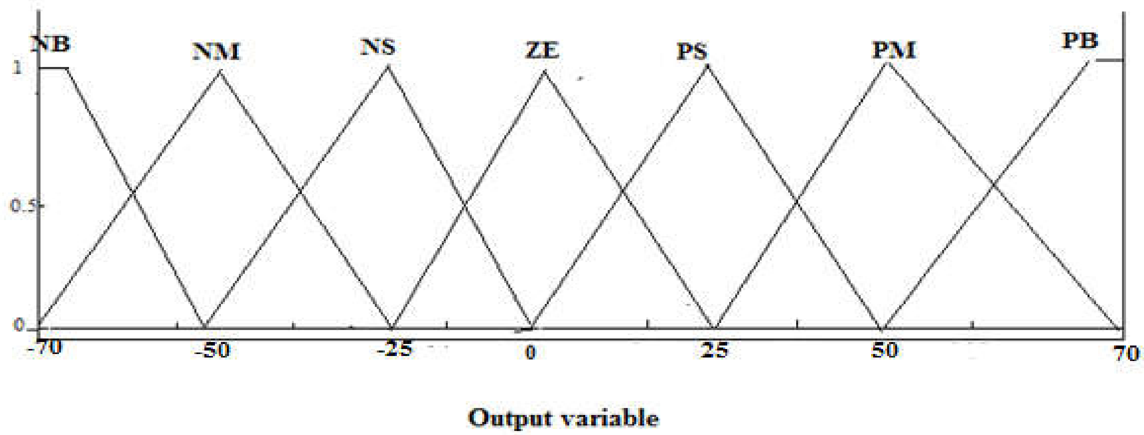


Figure 3.7 Output control variable membership function plot

Note that the universe of discourse of output variable is always set to cover a larger range. In this work it is set to about -70 to 70 so as to accommodate larger control area.

The next step is the formulation of fuzzy rule base, that is, a set of rules that relates a set of given input variable values into a set of required output variable values. The rule base formation is based on intuition, i.e., how an expert view the way the controller should affect the robot manipulator itself. For example in this work, if *angle error(e) is negative big(NB) and the derivative angle error(e) is negative big(NB) then Force (F) is positive big(PB)*. This is one of many possible fuzzy rules used in this work. Several rules of the type above were formed for each of the inputs. A total of 49 possible control signals are to be sent to the system depending on the degree of variation of error angle and its derivative as shown in Table 3.3

Table 3.4 Fuzzy Rules Base

e\e	NB	NM	NS	ZE	PS	PM	PB
NB	**PB**	**PB**	**PB**	**PB**	**PM**	**PS**	**ZE**
NM	**PB**	**PB**	**PB**	**PM**	**PS**	**ZE**	**NS**
NS	**PB**	**PB**	**PM**	**PS**	**ZE**	**NS**	**NM**
ZE	**PB**	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**
PS	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**	**NB**
PM	**PS**	**ZE**	**NS**	**NM**	**NB**	**NB**	**NB**
PB	**ZE**	**NS**	**NM**	**NB**	**NB**	**NB**	**NB**

The area highlighted in the Table 3.3 above is the consequents of the different situation of the two inputs. They represent what should be done should any of the input situations happened (antecedents). After building the fuzzy controller on MatLab the fuzzy is then given a name with an extension (.fis). The name given to it in this work is **grobot4.fis**.

The next stage is to incorporate the fuzzy controller in the system model developed earlier using Simulink environment as shown in Figure (3.8 and 3.9)

3.7Simulation Diagram

Figures (3.8 and 3.9) are the Simulink model of the system under Fuzzy controller and PID controller. From the Simulink model it can be seen that system is a single input and a single output, this is because analysis of the system is done with each joint controlled separately by taking each input to the system (U1 or U2) alone. Putting Θ_2 to a desired position, the second movable active joint of the arm is considered with zero input while motor (mc2) is inactive but mass of the motor was considered as part of the system).However, in controlling the second angle Θ_3, first motor is considered with zero input while motor (mc1) is considered inactive but mass of motor considered as part of the system.

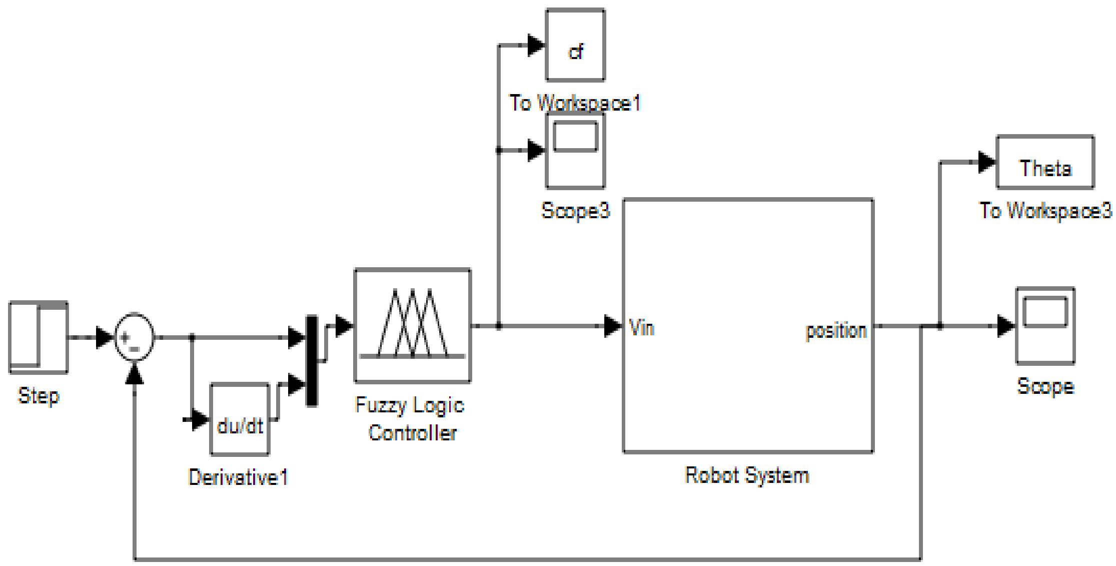


Figure 3.8 Fuzzy Control Simulink Model

Figure 3.8 is the fuzzy control simulink setup for controlling the gymnastic robot. A step input is the initial input to the system, the fuzzy controller is a two input controller (error and derivative error). Fuzzy controller send a control signal to the robot system for control action to take place. Scopes (scope and scope3) in the setup are inserted to view the response of the system and the control signal respectively. Workspace in the setup are meant to export the related response of the system.

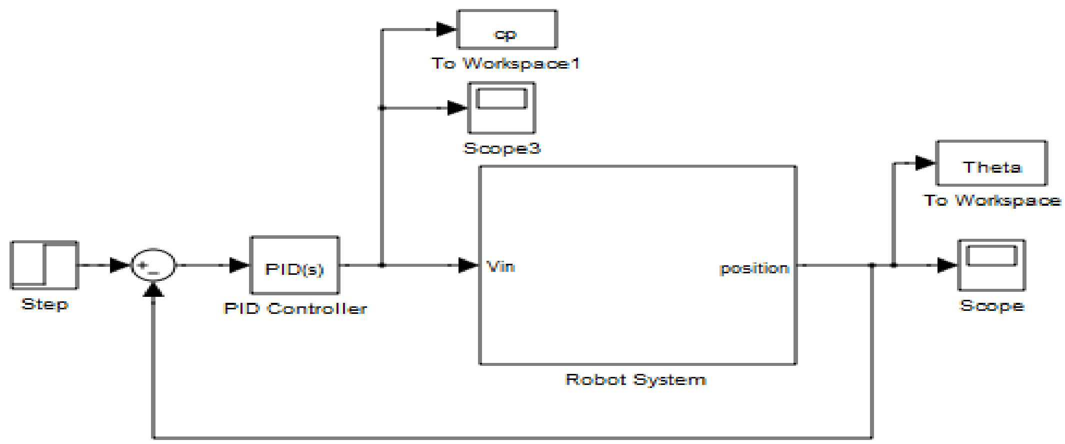


Figure 3.9PID Control Simulink Model

Figure 3.9 shows the PID control simulink setup used to compare with fuzzy control scheme for controlling the gymnastic robot. A step input is the initial input to the system. PID controller in this setup is tuned automatically using MatLab tuning to obtain control parameters.Scopes (scope and scope3) in the setup are inserted to view the response of the system and the control signal respectively. Workspace in the setup are meant to export the related response of the system.

This chapter concludes the method used in this work. The kinematic equation, dynamic equation, controllers design and as well the simulation setup were all discussed.

CHAPTER FOUR

SIMULATION RESULTs AND DISCUSSION

4.1Introduction

In this chapter, the system under Fuzzy and PID control are simulated individually using MatLab and results are presented. The system was tested under different desired output angle. The aim is to present the collections of results obtained for comparison. In this study, the results are analyzed base on some performance measures which provide a suitable benchmark for the comparison of the results.

4.2 Case I: Open Loop Simulation

Running the Simulink model of the Gymnastic robot without incorporating any of the controllers we have designed, the response of the system is shown in Figure 4.1. Therefore, from response observed, there is need to control the system if a desired position is required.

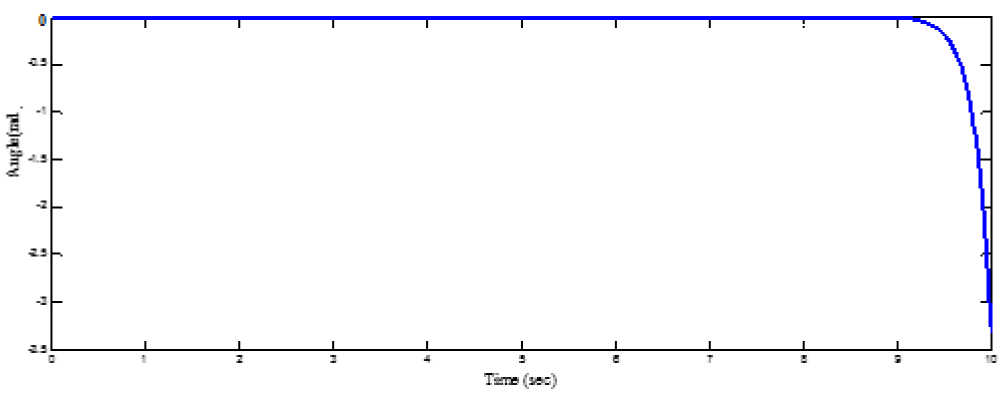


Figure 4.1 Open Loop Response of the Gymnastic Robot

The controllers were tested under various output conditions.

4.3Case I: For a Test Output of 11.5°

For a desired output of 0.2 rad(11.5°), the system was run under Fuzzy control and PID control. Control angles Θ_2 and Θ_3, are represented with below response shown in figures (4.1& 4.3) respectively and table 4.1 was obtained;

Table 4.1: PID vs. FLC Performance Table of Angle (Θ_2& Θ_3)

S/NO.	**PARAMETER**	**FLC (Θ_2)**	**PID (Θ_2)**	**FLC (Θ_3)**	**PID (Θ_3)**
1.	Rise Time	1.1 sec	0.38 sec	1.1 sec	0.38 sec
2.	Settling Time	2.8 sec	1.3 sec	2.4 sec	1.35 sec
3.	Steady State error	0.00	0.02	0.00	0.02
4.	Percentage Overshoot	0.00%	21%	0.00%	21%
5.	Control variable	28.9	55	11	21

The graphical response representing table 4.1 is shown is figures 4.1, 4.2, 4.3 and 4.4

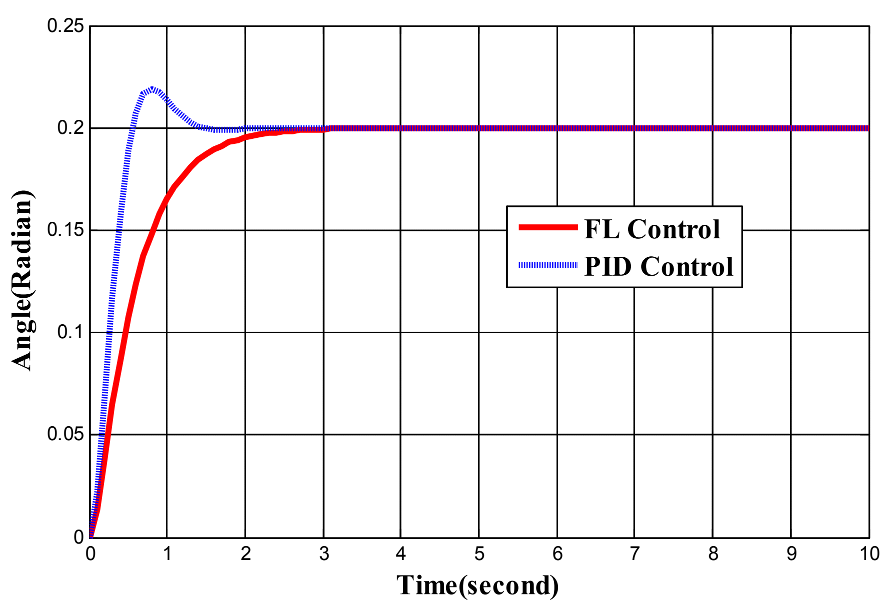


Figure 4.2 PID vs. FLC Response on 0.2 rad (11.5°) (Θ_2)

The Fuzzy and PID control signals for positioning Θ_2 is shown in figure (4.2) below,

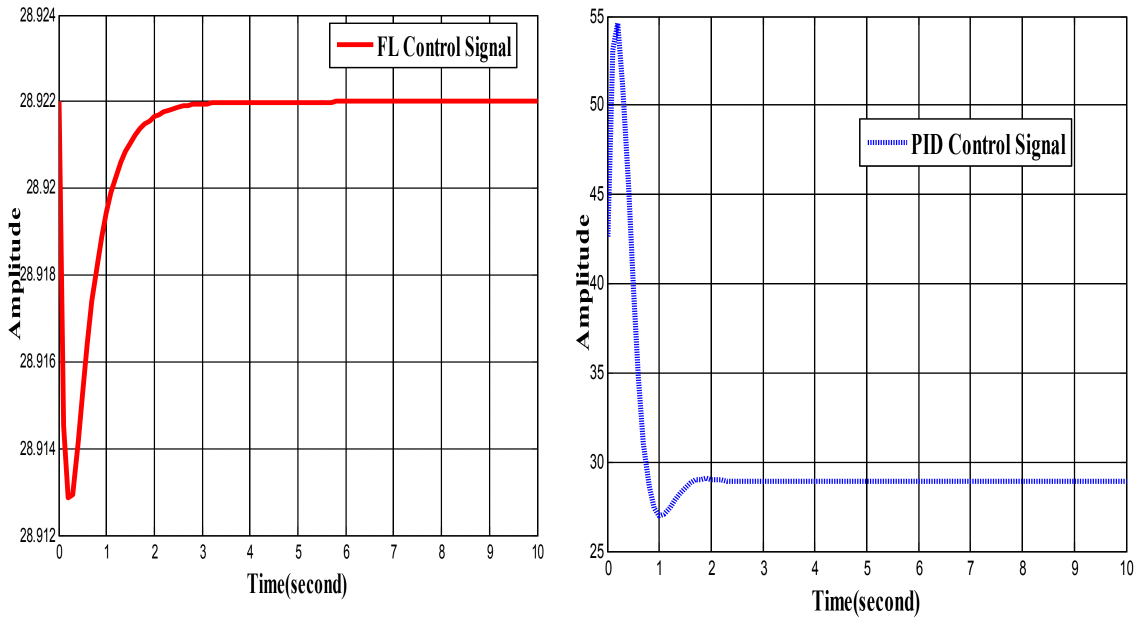


Figure 4.3 PID and. FLC ResponseControl Signal on 0.2 rad(11.5°)(Θ_2)

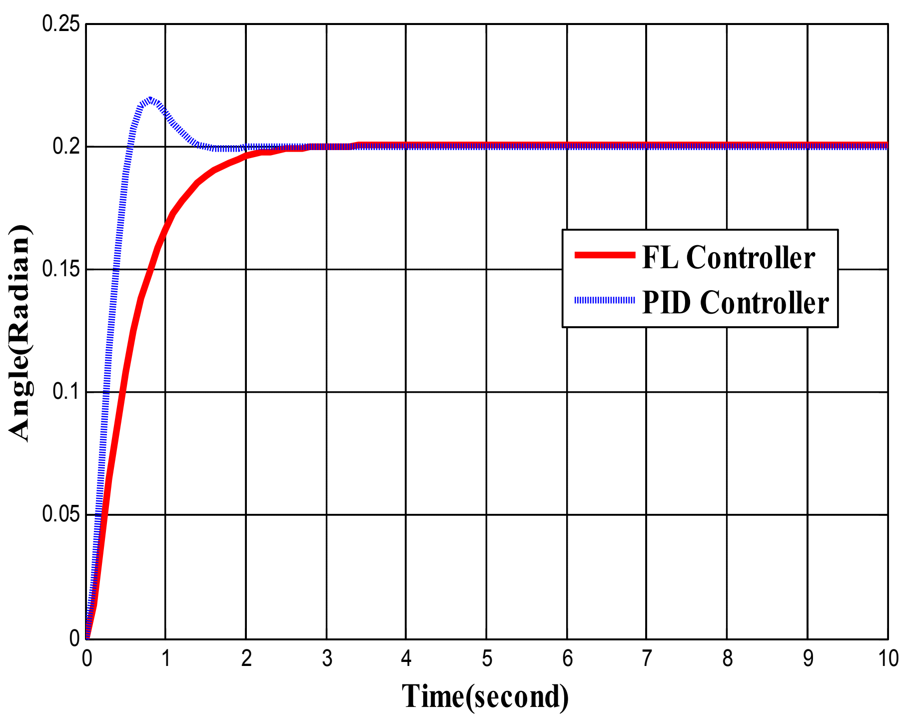


Figure 4.4 PID vs. FLC Response on 0.2 rad(11.5°)(Θ_3)

Fuzzy and PID control variable of $\Theta_3$is shown in figure (4.4) below,

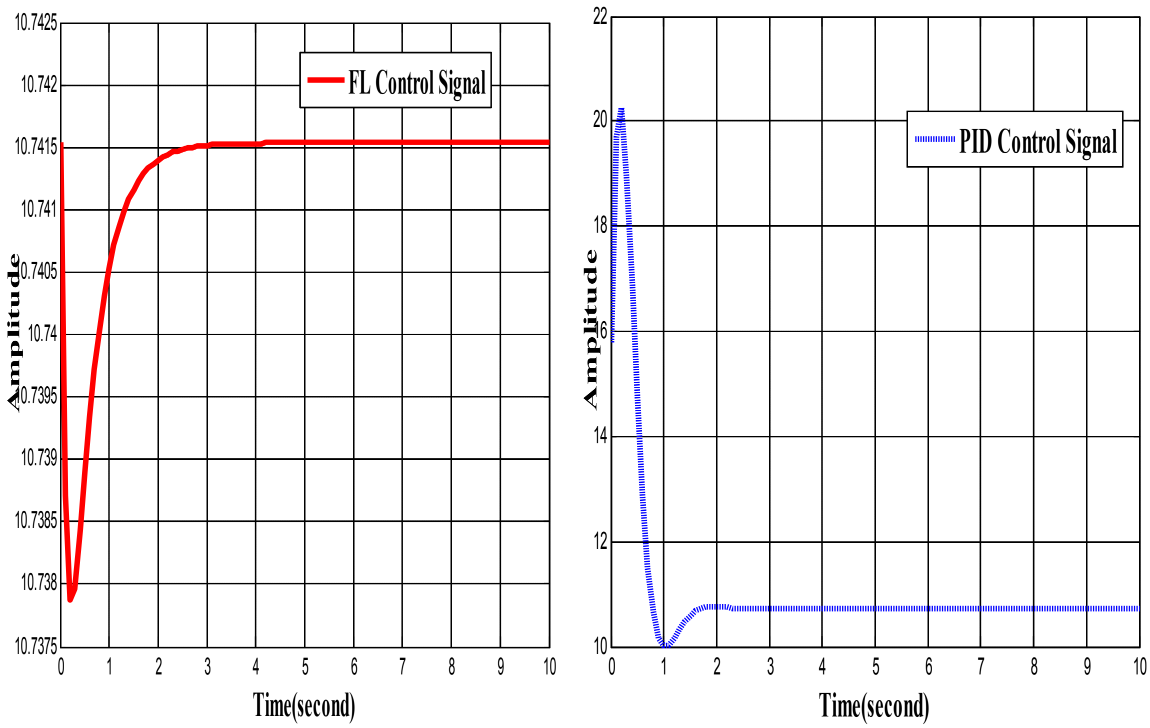


Figure 4.5 PID and. FLC Control Signal on 0.2 rad(11.5°) (Θ_3)

The performance measures of the system under FLC and PIDcontrol shown in table 4.1 shows fuzzy controller is the better controller when performance measures of steady state error and overshoot are considered. But PID shows a better response when settling time and rise time are considered.

4.4Case II: For a Test Output 28.3°

However, for a desired output of 0.5 rad(28.3°), the system was run under Fuzzy control and PID control. Performance of the controller with respect to control angles Θ_2 and Θ_3 are presented in table 4.2

Table 4.2: FLC and PID Performance Table of Angle (Θ_2& Θ_{3S})

S/NO.	PARAMETER	FLC (Θ_2)	PID (Θ_2)	FLC (Θ_3)	PID (Θ_3)
1.	Rise Time	2.0 sec	1.5 sec	2.0 sec	1.3 sec
2.	Settling Time	3.7 sec	2.7 sec	3.6 sec	2.7 sec
3.	Steady State error	0.00	0.07	0.00	0.07
4.	Percentage Overshoot	0.00%	16%	0.00%	16%
5.	Control variable	69.8	135	25.9	50

The graphical response with respect to table 4.2 is shown is figures 4.5, 4.6, 4.7 and 4.8

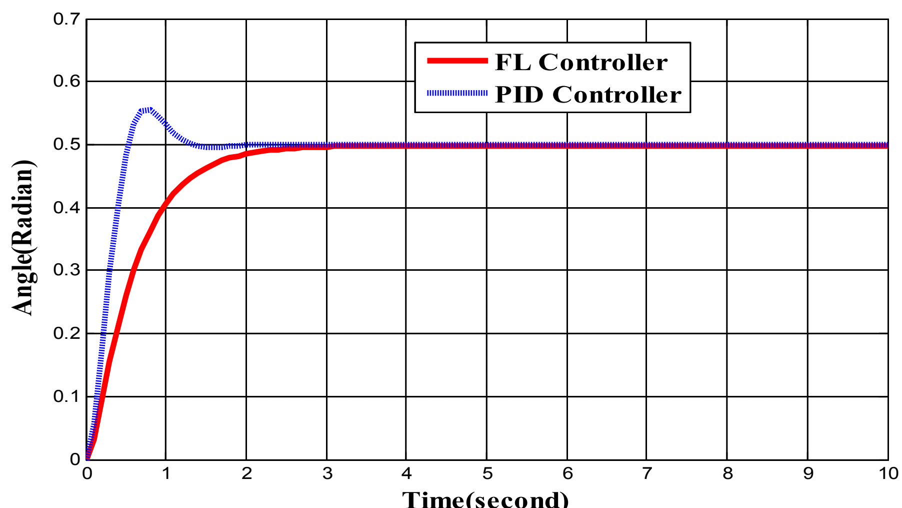


Figure 4.6 PID vs. FLC Response on 0.5 radians (28.6°) of Θ_2

The controllers' output signal in positioning Θ_2 is shown in figure 4.6

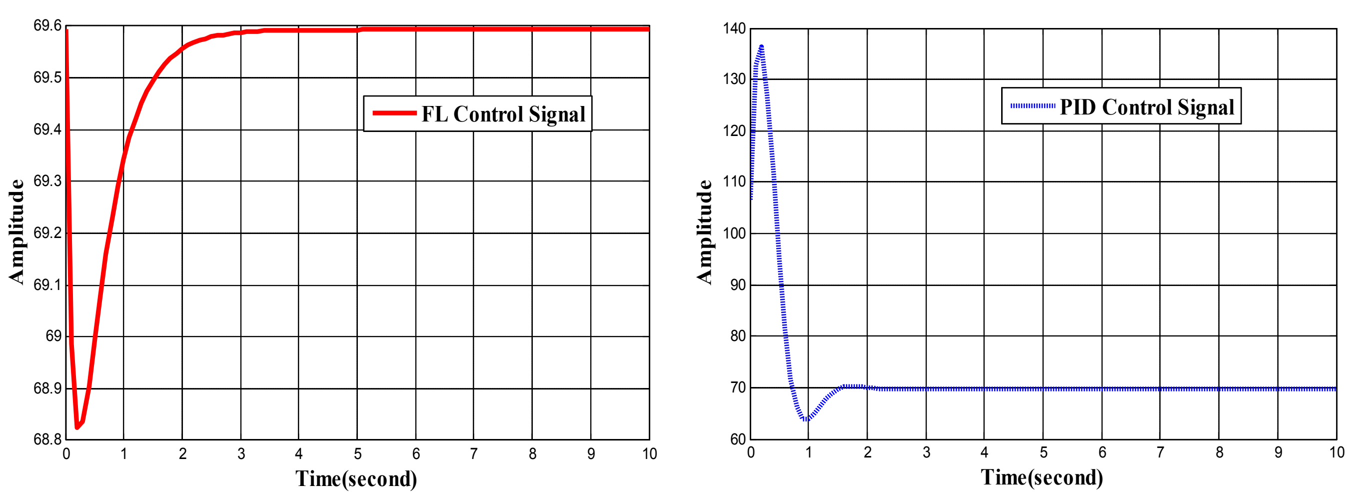


Figure 4.7 PID and. FLC Control Signal on 0.5 radians (28.3°) of Θ_2

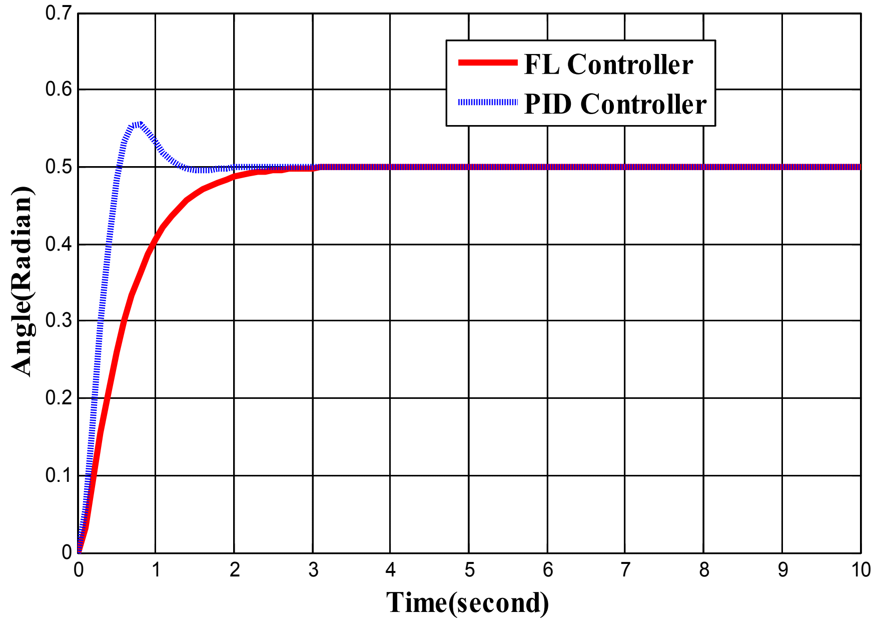


Figure 4.8 PID vs. FLC Response on 0.5 radians (28.6°) of Θ_3

Fuzzy and PID controllers' output signal in controlling Θ_3 is shown in figure 4.8

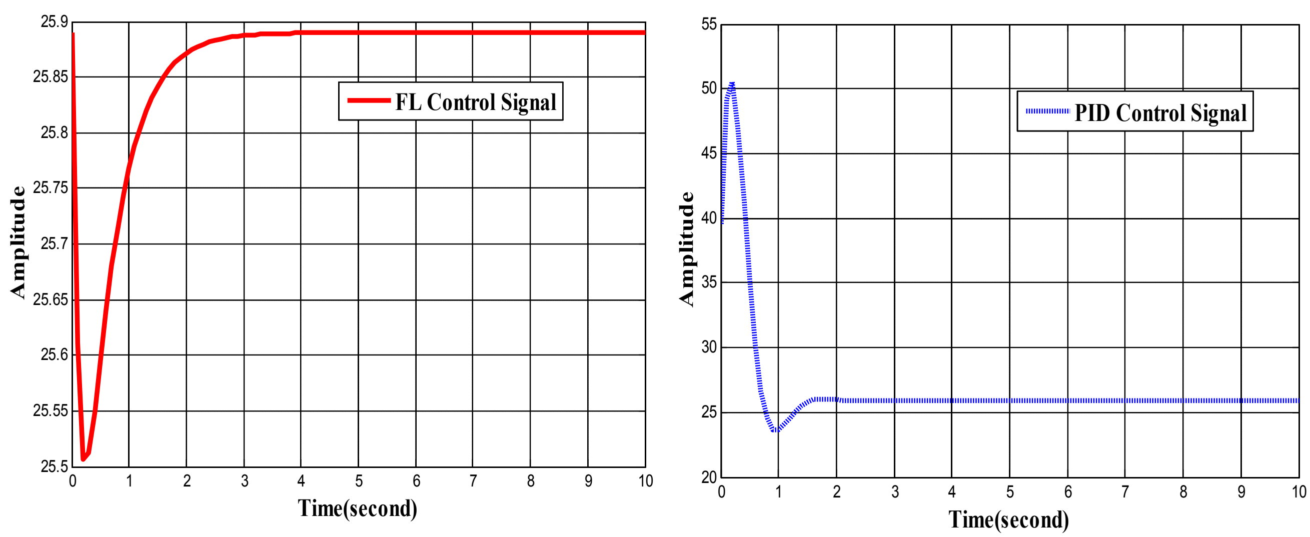


Figure 4.9 PID and. FLC Control Signal on 0.5 radians (28.6°) of Θ_3

The performance measures of the system under FLC and PID control is shown on table 4.2 proves that Fuzzy controller is the better controller when performance measures of steady state error and overshoot are considered. But PID shows a better response when settling time and rise time are considered.

4.5Case III: A Test Output of 57.3°

For an output of 1.0 rad(57.3°), the system was tested under both fuzzy and PID control scheme. The performance measure of the system under Fuzzy and PID controllers are shown in table 4.3

Table 4.3: FLC and PID Performance Table of Angle (Θ_2& Θ_3)

S/NO.	**PARAMETER**	**FLC (Θ_2)**	**PID (Θ_2)**	**FLC (Θ_3)**	**PID (Θ_3)**
1.	Rise Time	1.3sec	0.3sec	1.3sec	0.3sec
2.	Settling Time	2.5sec	1.35sec	2.5sec	1.3sec
3.	Steady State error	0.00	0.23	0.003	0.18
4.	Percentage Overshoot	0.00%	21%	0.00%	22.5%
5.	Control variable	122.5	270	55.5	80

The pictorial response of the system with respect to table 4.3 is shown in figures 4.9, 4.10, 4.11 and 4.12.

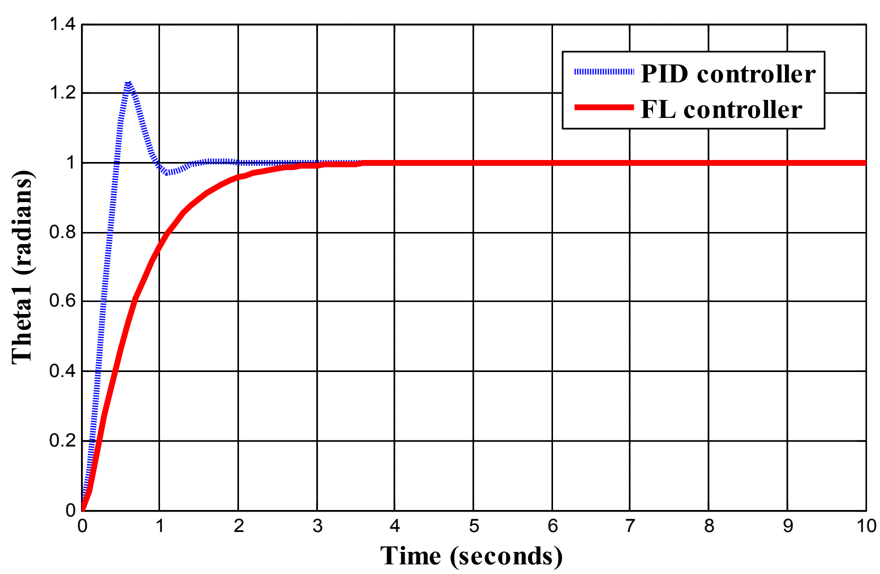


Figure 4.10 PID vs. FLC Response on 1.0 radians (57.3°) of Θ_2

The Fuzzy and PID controller output signal in positioning $\Theta_2$is shown in figure 4.10

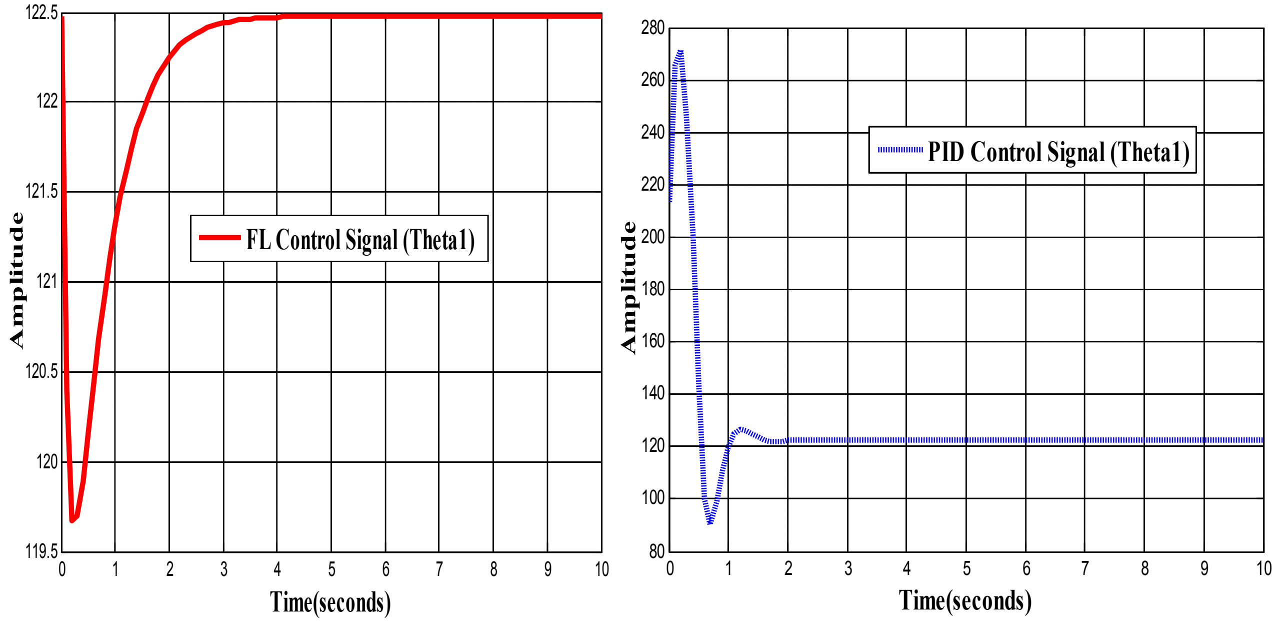


Figure 4.11 PID and. FLC Control Signal on 1.0 radians(57.3°) of Θ_2

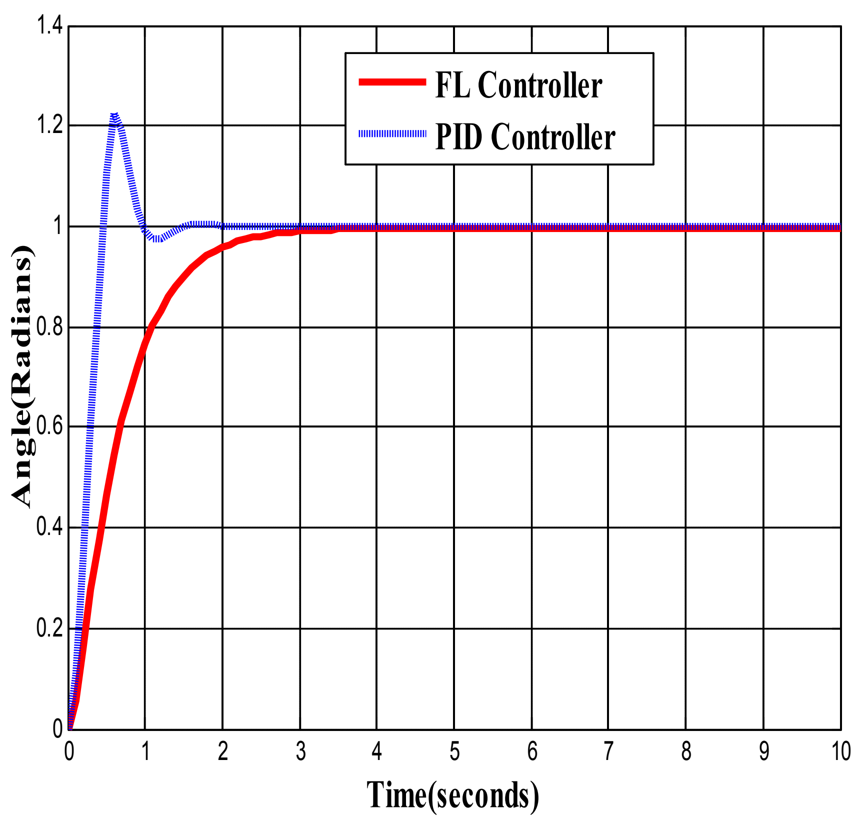


Figure 4.2 PID vs. FLC Response on 1.0 rad (57.3°) of Θ_3

The Fuzzy and PID controllers' signal used in positioning Θ_3 is shown in figure (4.93) below;

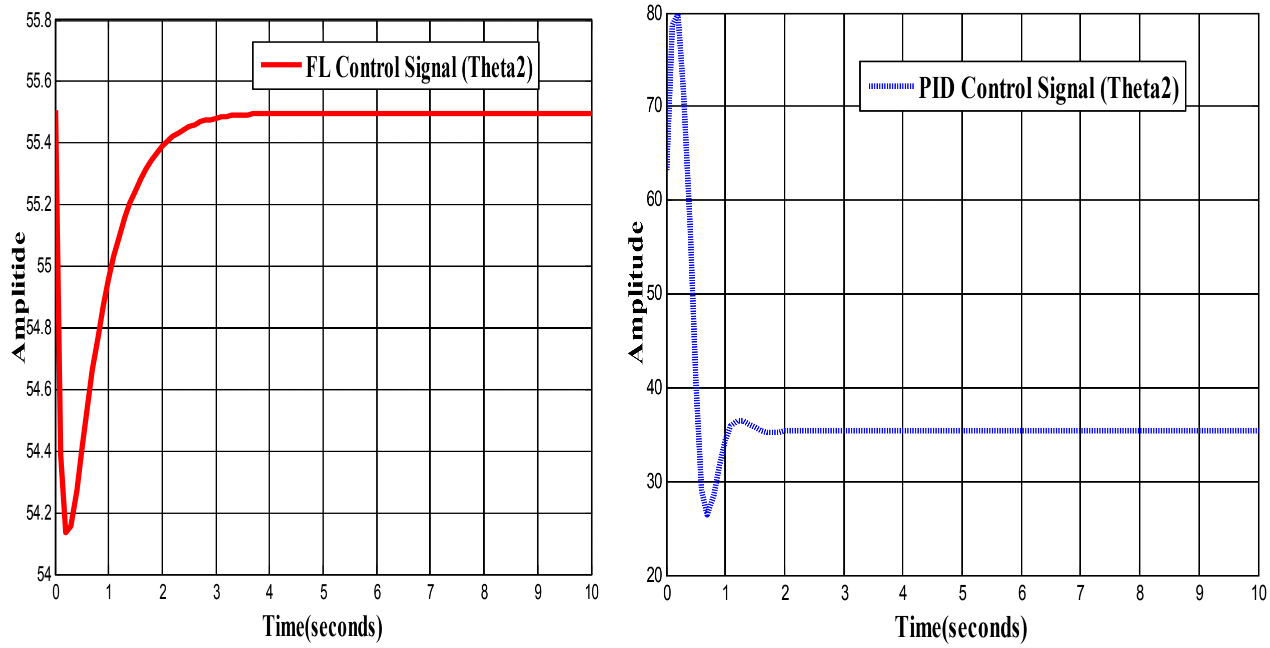


Figure 4.13 PID and. FLC Control Signal on 1.0 rad(57.3°) of Θ_3

Table 4.3 summarizes the performance of both Fuzzy and PID controllers in controlling the robot system. The performance table proves Fuzzy controller is the better controller when performance measures of steady state error and overshoot are considered. But PID shows a better response when settling time and rise time are considered.

4.5Case IV: A Test Output of 85.9°on Square Input

In this case, a square input is used rather than a step inputon a test output of 1.5 rad(85.9°), the system was tested under both fuzzy and PID control scheme. The performance measure of the system under Fuzzy and PID controllers are shown in table 4.4. Both controllers have much greater gain in controlling the system, rise time of PID is still small but the gain is much and can be very expensive to realize in practical.

Table 4.4: FLC and PID Performance Table of Angle (Θ_2& Θ_3)

S/NO.	PARAMETER	FLC (Theta2)	PID (Theta2)	FLC (Theta3)	PID (Theta3)
1.	Rise Time	2.0 sec	0.27 sec	2.0 sec	0.27 sec
2.	Settling Time	3.7 sec	2.7 sec	3.6 sec	2.7 sec
3.	Steady State error	0.00	0.07	0.00	0.07
4.	Percentage Overshoot	0.00%	44.7%	0.00%	68%
5.	Controller Gain	145	410	55	150

The pictorial response of the system with respect to table 4.4 is shown in figures 4.13, 4.14, 4.15 and 4.16.

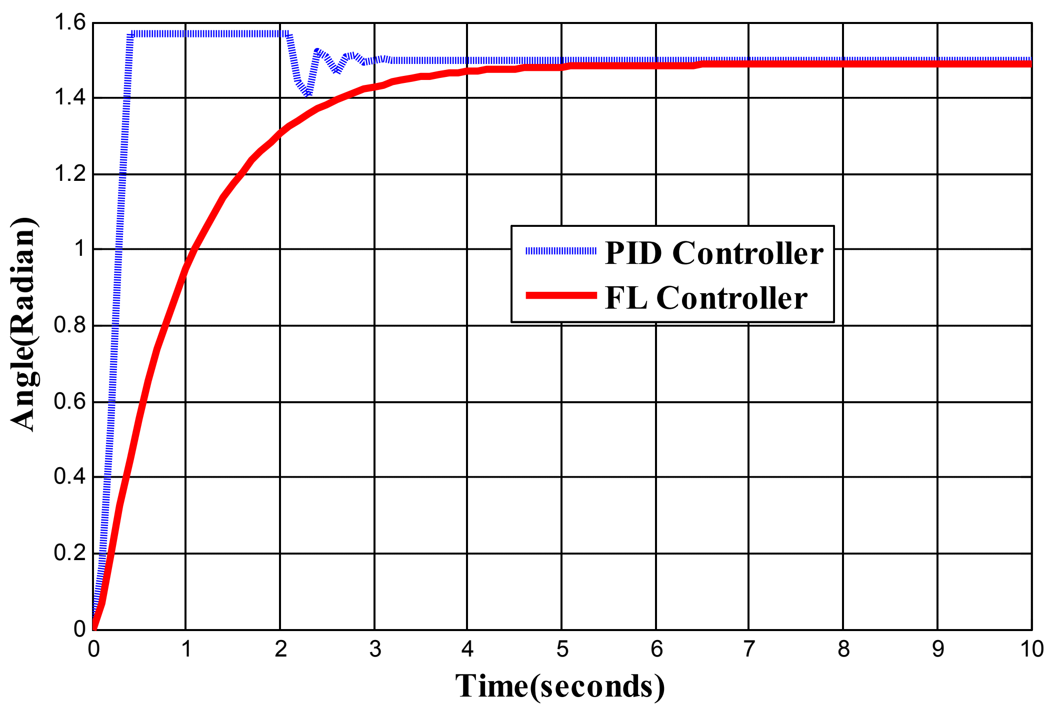


Figure 4.14 PID vs. FLC Response on 1.5 rad (85.9°) of Θ_2

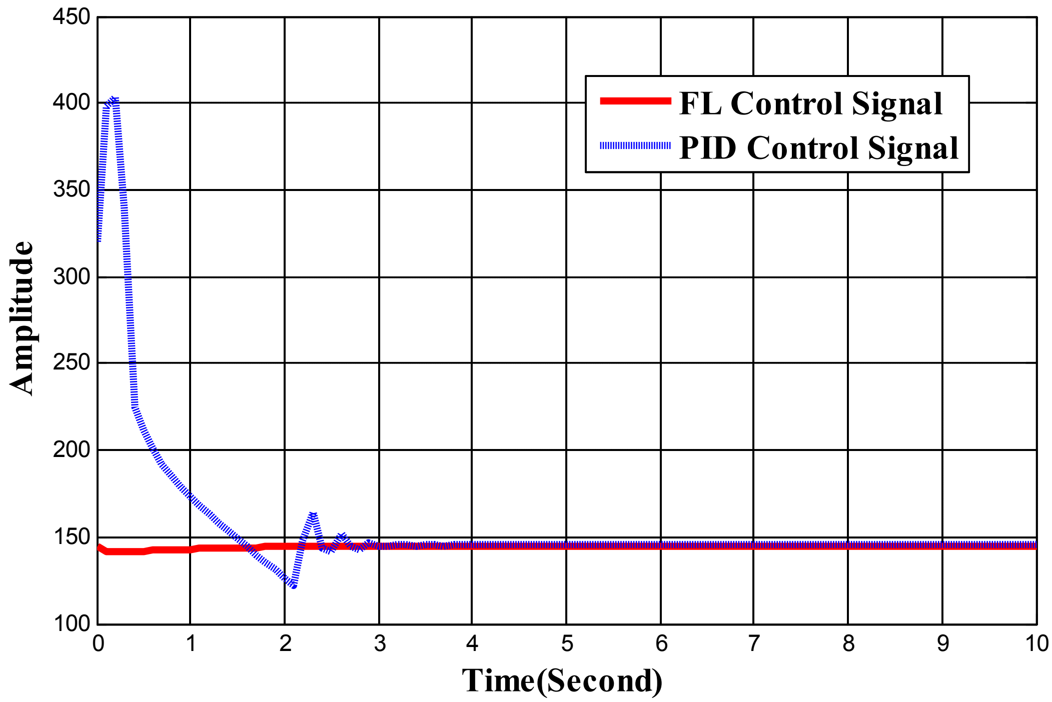


Figure 4.15 PID vs. FLC Control Signal on 1.5 radians (85.9°) of Θ_2

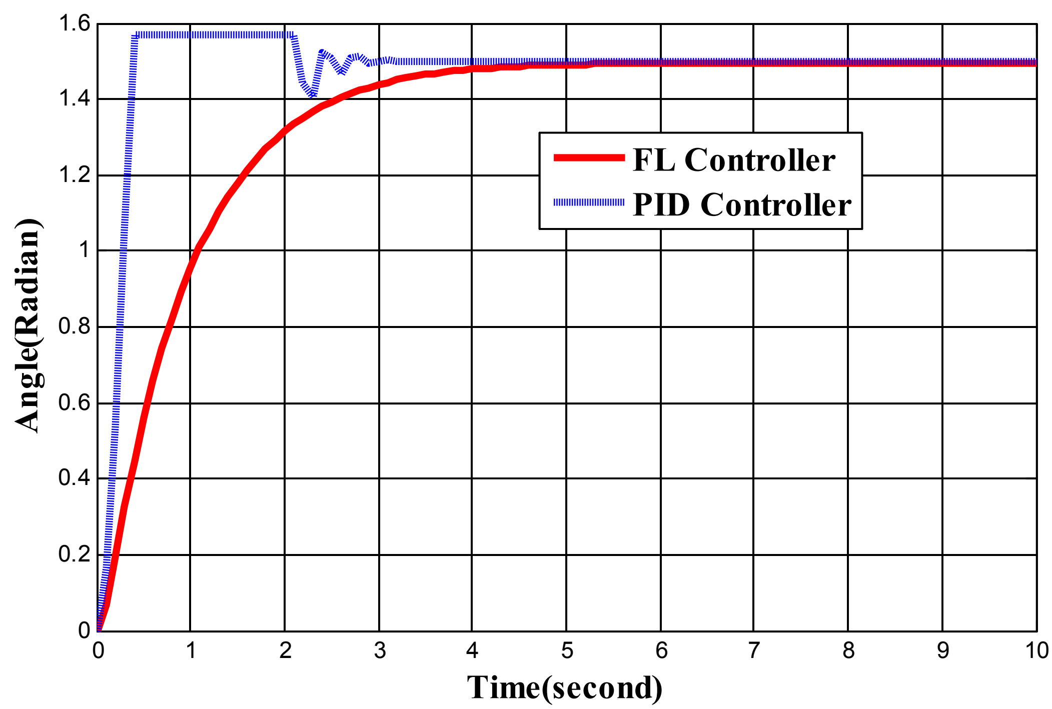


Figure 4.16 PID vs. FLC Response on 1.5 rad (85.9°) of Θ_3

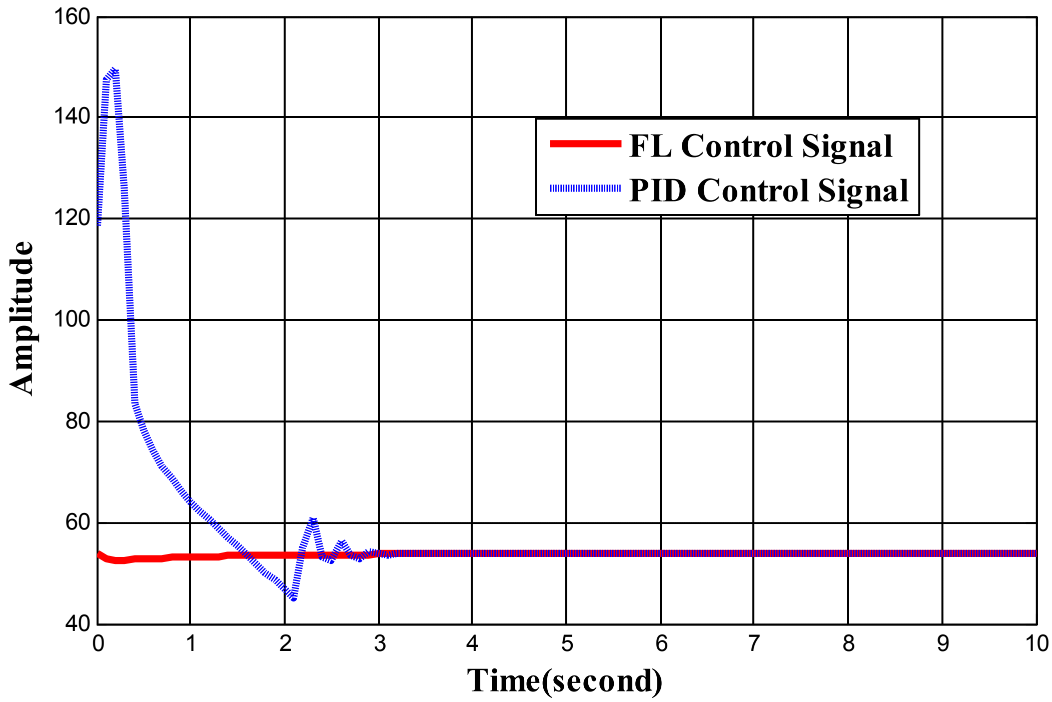


Figure 4.17 PID vs. FLC Control Signal on 1.5 radians (85.9°) of Θ_3

4.6Discussion

Tables 4.1, 4.2 and 4.3 summarizes all the characteristics of the responses obtained from the system controlled by Fuzzy controller and conventional controller (PID). Controllers are considered under various test outputs using step input.The system was run under 0.2, 0.5 and 1.0 radians desired output. Table 4.4 shows the performance of both controllers when a square input with a desired output of 1.5 radians. Base on the performance measures used in the analysis for various response obtained, it can be seen that PID settled faster than FLC in all the desired outputs. However, Fuzzy logic controller proved to be more efficient when considering steady state error and percentage overshoot.

In conclusion, FLC is a better controller in this application because of the absolute need to have an efficient tracking of input to the system. Whereas, the performance of conventional PID tends to saturate as the output angle increase.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1Introduction

This work has presented a study for controlling gymnastic robot position using FLC. The process depends on two main sides; the first one is the Fuzzy controller design of the manipulator while the second one comparing the fuzzy control performance and the system tuned PID controller.

5.2Conclusion

The research has presented the comparison between Fuzzy logic controller and PID controller for a three (3) links gymnastic robot using computer simulation under different conditions. It can be concluded that:

The adopted gymnastic robot model which is a Multi Input Multi Output (MIMO) system was analyzedas Single Input Single Output (SISO) control problem.

The Fuzzy logic controller was designed with the help of Simulink on MatLab platform.

Finally, the comparison between FLC and system tuned PID controller was carried out for position control of gymnastic robot and from the results obtained; it was observed that the two control schemes performed well in the control of arm angle of the gymnastic robot. The FLC performed much better when considering the steady state error and the overshoot of the responses obtained however, PID shows slightly superior performance in terms of rise time and settling time. In view of this, Fuzzy logic controller can be considered a better controller for some of applications of robot manipulator system as these applications give priority to accurate tracking of the reference input. Nonetheless, the proposed controller could be judged a valuable control tool for robot systems. Hence, the objectives of the thesis are achieved.

5.3 Contributions

I. Gymnastic robot is known to be Multi Input Multi Output (MIMO) system but analysis and control was done by making use of Single Input Single Output (SISO) to represent the system and control target is achieved.

II. Gymnastic robot is controlled using human intelligent in the case of paralyzed patient were motion is caused by pulse sent by the brain, but work designed a fuzzy controller to control the system.

III. Gymnastic robot usually controlled with some oscillation in response due to the strong coupling between its links, this work presented control for the system free of oscillation.

5.4 Recommendations

1. Fuzzy logic control should be simulated on higher degree of freedom for gymnastic robot manipulators.
2. Individual linkfuzzy control of gymnastic robot should be compared with coupled fuzzy control to see if there may be any some difference.
3. Practical implementation of both FLC and PID controller on a practical system will provide a greater insight in the understanding of these controllers.
4. Also provision of auto tuning of the fuzzy just like system tuned PID will be of great importance in the simplification of fuzzy controller design.

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