CONTROL OF FLEXIBLE MANIPULATOR USING PID-BASED IDENTIFIED MODEL FROM PID CONTROLLERS

NURADDEEN IBRAHIM ISAH

SPS/15/MEE/00020

M.ENGELECTRICAL

(CONTROL AND INSTRUMENTATION)

A DISSERTATION SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING, SCHOOL OF POSTGRADUATE STUDIES, BAYERO UNIVERSITY, KANO, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTERS OF ENGINEERING

JANUARY, 2020

DECLARATION

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

……………………………………..

NURADDEEN IBRAHIM ISAH
SPS/15/MEE/00020

CERTIFICATION

This is to certify that the research work for this desertation and the subsequent write-up by Nuraddeen Ibrahim Isah - SPS/15/MEE/00020 was carried out under my supervision.

………………………………………

Dr. Amir Abdullahi Bature
(SUPERVISOR)

………………………………………

Prof. Nuraddeen Magaji
(HEAD OF DEPARTMENT)

APPROVAL

This thesis has been examined and approved for the award of Masters of Electrical Engineering (Control and Instrumentation).

……………………….. ………………………….

External Examiner Signature/Date

………………………... …………………………..

Internal Examiner Signature/Date

……………………………………………….

Supervisor Signature/Date

……………………………………………….

Head of Department Signature/Date

……………………………………………………………….

Board of the School of Postgraduate Studies Signature/Date

ACKNOWLEDGEMENT

In the name of Allah, the Beneficent, the Merciful. May Allah bless our Prophet Muhammad (SAW), his family and his companions. All praises are to Almighty Allah (SWA) that made things possible for me during the period of conducting and writing this thesis and for all that He has done to me in life. I would like to express my gratitude to some people who kindly contributed towards the achievement of this thesis project, that is to say, without their co-operation and contribution the thesis work could not have been done successfully.

First, my deepest special thanks goes to my able supervisor Dr. Amir Abdullahi Bature, who gave his guidance in correcting all work undergone in the dissertation. Despite all of his tight schedules he had offered to be a tireless effort in guiding and ensuring that the thesis is being written in a required standard form.

Subsequently, my special thanks goes to Jude Aienoleyboise Osaweremen, the entire staff of Electrical Engineering Department and all other staff in general for the academic contribution given to me throughout my stay at Bayero University, Kano.

My special thanksgiving and endless gratitude goes to my mother Hajiya Bilkisu, my late father Mallam Isah Ibrahim, and my brothers and sisters. My special gratitude goes to my wife Hajiya Radiyya Sa'id Abdulkadir for her patience, support, and understanding during my studies.

Finally, to all my friends, course mates and colleagues, I wish you long life and prosperity.

DEDICATION

This research work is dedicated to the memory of my late father Mallam Isa Ibrahim. May Allah grant his gentle soul a perfect peace, forgive his shortcomings and make Jannah his final abode, Ameen.

TABLEOF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

k: Discrete time index

$u(k)$: System input at discrete-time k

$y(k)$: Measured system output at discrete-time k

$\underline{\theta}(k)$: Unknown parameter vector to be estimated

$\hat{\underline{\theta}}(k)$: Estimate of $\underline{\theta}(k)$

$\varphi(k)$: Vector of input and output signals, and possibly their delayed signals

$\varepsilon(k)$: Residual

$\hat{y}(k)$: Estimated output signal

K_p: Proportional gain

K_i: Integral gain

K_d: Derivative gain

P: Proportional controller

PI: Proportional Integral controller

PID: Proportional Integral Derivative controller

FM: Flexible Manipulator

LS: Least Squares

LQR: Linear Quadratic Regulator

LQG: Linear Quadratic Gaussians

ABSTRACT

This research presented an efficient control scheme for Flexible Manipulator with an identified controller designed from the combination of the desired characteristics of two PID controllers. The identifiedmodel controller is capable of providing more accurate and precise hub angle step response thanthe PID controllerswith a decrease of 73% settling time of PID1 and a decrease of 81% overshoot of PID2. The identified controller provided a better tip deflection step responsethan PID2 with a decrease of 17% and 73% for the settling time and overshoot respectively. The identified controller is capable of providing more accurate and precise hub angle response when tested with a bang-bang signal than both PID controllers with only an increase of 7% overshoot to the reference signal as compared to PID1 with a decrease of 79% to the reference signal and PID2 with an increase of 29% to the reference signal. The simulation was done on MATLAB R2015a simulink environment using System Identification Toolbox and the result shows that better performance was achieved using the identified controller because of its robustness to track different input signals to the system.

CHAPTER ONE

INTRODUCTION

1.1 Study Background

Control of flexible manipulators has been an interesting field of research for the past two decades. A significant increase in the number of researches in control of flexible manipulators has been reported. This is due to increase in demand for a high speed industrial robot[1]. The need for a light-weight robot, for industrial applications increases significantly, due to their advantages over heavy weight robot. Some of the advantages of flexible light weight robots are; they can easily be driven by small sized actuator, they consumed less electrical power, high-speed operation, low cost and have light weight[1]. Many novel robotics manipulators applications needs lighter robots that consumed less amount of power for their operation. These types of robot are widely used for space robot, micro-surgery operation and nuclear plant maintenance [2]. Figure 1.1 shows a pictorial diagram of a flexible manipulator

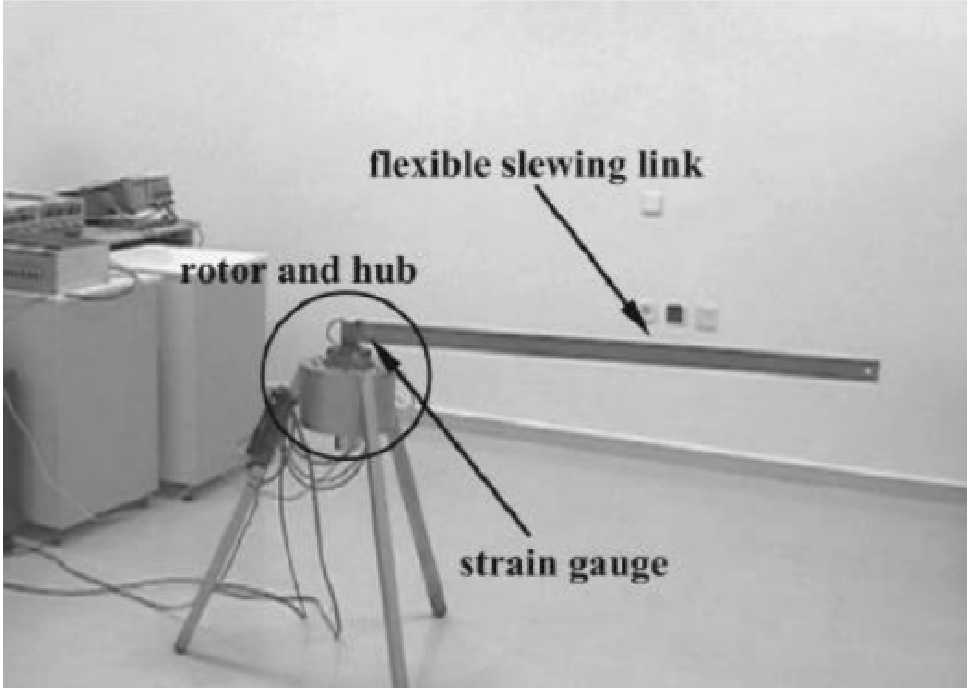

Figure 1.1 Flexible Manipulator [2]

However, they have some disadvantages due to elasticity of the system and high vibration which make their control design very complicated[3]. To achieve precise hub angle positioning and low tip deflection is a complex task especially for the system with varying payload. This is due to their flexible nature which is associated with high vibration and tip deflection during operation. The deflection increases with inclusion, of a payload attached to the link [4]. Figure 1.2 shows a schematic diagram single-link flexible manipulator system.

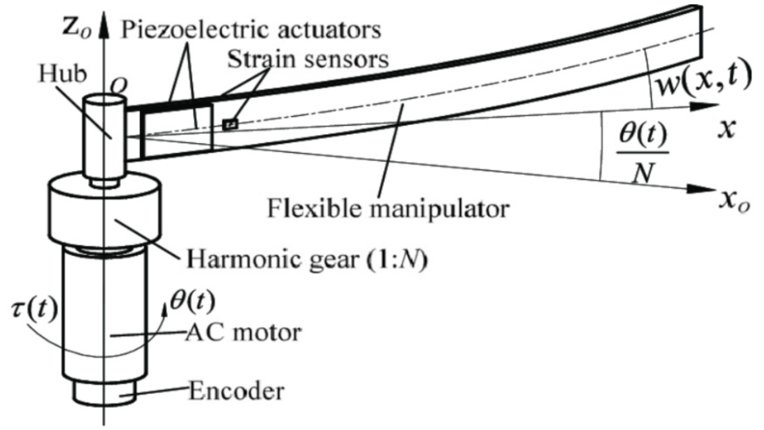

Figure 1.2 Schematic diagram of a flexible Manipulator[5]

There are two main issues that create problems in the design of flexible manipulator controllers. These are: problems due to

- high order of the systems
- non-minimum phase dynamics of the system that exist between the tip position and the applied torque at the hub of the system [6].

1.2 Problem Statementand Significance of Study

A flexible manipulator system is a system that operates with high vibration and tip deflection. Moreover, the vibration and tip deflection becomes highly significant when a payload is attached to the flexible link. An efficient control scheme is needed to achieve a precise hub angle positioning with low tip deflection. In addition, the control design is difficult due to high order and non-linearity of the system [7].

As a result of the above mentioned problems, researchers implemented many different control methods to solve these problems. Such as pole placement [8], Linear Quadratic Gaussians (LQG) [9], PID controllers [10], adaptive control techniques [11], neural networks and fuzzy logic control algorithms.[14-20]. In this project, a PID-based identified model from the PID controllers is obtained and applied to the system in order to give a precise hub angle and further suppress the tip deflection.

1.3 Aim and Objectives

The aim of this project is to develop an identified model controller for a single link flexible manipulator. To achieve this aim, the following objectives were set;

1. Designing two PID controllers with different desired characteristics.
2. Designing an identified model controller for the system.
3. Comparing the performance analysis of the PID controllers with the identified controller to the plant model adopted for the flexible manipulator system.

1.4 Methodology

The methods to be adopted in this research are represented in the following steps:

1. The model of the system was adopted as described from [22]
2. Auto tuning based on desired characteristics was used to design two PID controllers with PID1 having a slow response and no overshoot and PID2 having a fast response and overshoot
3. Matlab/Simulation R2015a is used to obtain input/output of the system using each PID controller
4. Matlab/Simulation result of the PID controllers was used to design a proposed controller
5. Matlab/Simulation result is used to obtain input/output of the system using the proposed controller
6. Comparison of results of the PID controllers and the identified model.

1.5 Scope and Limitation

The scope of study is limited to a single link flexible manipulator. The implementation of the control scheme is limited to simulation.

1.6 Thesis Organization

The thesis report was organized as follows.Chapter one presents the introduction, aims and objectives, methodology, scope and limitation.Chapter two presents the overview ofPID theory,literature review of the research. Chapter three contains the design procedures ofthe PID controllers and the proposed controller. Chapter four contains simulation results and discussion, while chapter five presents summary, conclusion and recommendations for future research work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In this chapter,PID theory will be discussed andreview of past work reported by various researchers on PID controllers andLeast Squares (LS) parameter estimator as one of the most popular estimation algorithms.

2.2PID Theory and Previous Work

PID (Proportional – Integral - Derivative) control is one of the classical control methods that is frequently used nowadays especially in industry because of its simple structure and working stability. PID controllers are the most commonly used in industry, as a result of their limitations experience by academicians and industrialists.

PID algorithm is used to compute the control signal that activates the real system based on the following formula.

$$u(t) = K_p e(t) + K_I \int e(t)dt + K_D \frac{d}{d_t} e(t) \qquad (2.1)$$

$$e(t) = r(t) - y(t) \qquad (2.2)$$

where u(t) is control signal, e(t) is error and y(t) is output response. Furthermore, K_p, K_D and K_I are PID parameters which need to be tuned. In this method, e(t) is the error variable that is reduced to zero upon parameter tuning. Thus the system response is adjusted to the desired reference. As shown from equation 2.1, u(t) control signal consist of three sums. The first one is product of e(t) error signal K_p which is proportional gain, and the second one is the product of K_I which is integral gain by integral of e(t), finally the last one is product of K_D which is derivative gain, and derivative of e(t). In general the effect of K_p, K_D and K_I gains which are the PID parameters on system response are shown in Table 2.1

Table 2.1 Effect of PID Parameters on System Response[13]

	Rise Time	**Overshoot**	**Settling Time**	**Steady State Error**
K_p	Reduce	Increase	Small Change	Reduce
K_D	Reduce	Increase	Increase	Eliminate
K_I	Small Change	Reduce	Reduce	Small Change

Improved versions of PID controllers were designed and implemented by researchers to make them more efficient. Some researchers came up with alternative controllers by combining PID control with resonant controllers for flexible structures in decision and control as in [24].

PID controller is the most dominating form of feedback in use today where more than 90% of all control loops are PID[10]. Most loops are in fact PI because derivative action is not used very often. Strength of the PID control is that it also deals with important practical issues such as actuator saturation and integrator windup. Beside the development of design methods for PID control, there are some difficult problems that remained to be solved such as there is no characterization of the process where PID control is useful.

2.2.1 PID with State Feedback Control

In [13],the researchers proposed the use of PID and State Feedback control methods to control the position and trajectory of a single-link flexible manipulator. The experimental results were compared for each control method. In the study, PID and state feedback control responses are similar; each control methods have advantages and disadvantages. Step responses of PID control method are more satisfactory than the state feedback control because it has less overshoot and less oscillation but has higher rise time than state feedback. The result shows that state feedback control slightly outperforms the PID control in controlling the position and trajectory of the single-link flexible manipulator.

2.2.2 PID Control with Genetic Optimisation

In [14],a genetic algorithm (GA) to optimize the parameters of a PID-based controller of the manipulator system in vertical motion was used. Genetic algorithms (GA) were used to develop controllers placed in the feedforward path, feedforward and feedback paths and with iterative learning control for control of rigid-body motion and flexible motion dynamics of the system. Input and output data from the simulation were collected and used with GA to obtain suitable controller parameters of the system. Simulation results of the response of the manipulator system with the developed controllers were presented and a comparative assessment of the performance of the developed controllers with PID, PID-PID and PID-ILC controller were provided.

Three different control methods (PID, PID-PID and PID-ILC) were used to test four outputs namely hub angle, hub velocity, end-point acceleration and end-point residual. For hub angle control, it was noted that PID and PID-PID gave the best maximum overshoot output and steady states output. The settling time for PID, PID-PID and PID-ILC controller were the same resulting to the good performance of the flexible manipulator. For hub velocity, end-point acceleration and end-point residual, it was notedthat PID control resulted in the best performance, followed by PID-PID control and PID-ILC. A similar trend is observed with the PID and PID-PID controllers, where the best reduction in the magnitude of vibration was achieved with PID-PID control compared to PID and PID-ILC.

2.2.3PID Control with LQR

In [15], investigations into the development of control schemes for end-point vibration suppression and input tracking of a flexible manipulator were presented. A constrained planar single-link flexible manipulator is considered and the dynamic model of the system is derived using the assumed mode method.

To study the effectiveness of the controllers, initially a Linear Quadratic Regulator (LQR) is developed for control of rigid body motion. This is then extended to incorporate a non-collocated PID controller for control of vibration (flexible motion) of the system.

It was noted that high performance in the reduction of vibration of the system was achieved using LQR with non-collocated PID control. This was observed and compared to the LQR controller at the first two mode of vibration. For comparative assessment, the levels of vibration reduction of the end-point acceleration were obtained as 37.14 dB and 8.04 dB at the first two mode of vibration respectively. Moreover, almost two-fold improvement in the end-point acceleration reduction was observed with LQR with non-collocated PID as compared to the LQR controller. However, as demonstrated in the end-point trajectory response, there was not much difference between LQR with non-collocated PID control and LQR controller in terms of speed of the response. Besides, the implementation of LQR with non-collocated PID required a large amount of design effort in order to determine the best PID parameters. Note that a properly tuned PID could produce better results thus, having a better reduction in the vibration.

2.2.4Fuzzy PID Control

In [16], a robust fuzzy-tuned PID controller for the trajectory tracking and vibration control of a flexible joint manipulator system (FJMS) with parametric uncertainties was proposed. Flexible joint manipulators are widely used in industry due to their flexibility, light in weight and fast response, low cost, and low energy consumption. The dynamic modeling via Euler-Lagrange equation for a single link FJMSwas presented first. By analyzing the characteristics of the high order linear system, the Fuzzy-Tuned PID control strategy was utilized. The parameters of classical PID controller are updated by the intelligent method of fuzzy logic. With the adaptivity to the parametric uncertainties from the system stiffness and moment of inertia, the contrived approach provides more efficient results compared to existing techniques in terms of vibration suppressions, time response, and overshoot.

The fuzzy-tuned PID controller technique was presented in this paper to resolve the problem of parametric uncertainties, vibration suppression, and end-point trajectory tracking of a flexible joint manipulator system (FJMS). The gains of PID controller were tuned by an intelligent method using fuzzy logic which adds robustness and adaptivity to the controller. The optimum results were obtained from fuzzy-tuned PID controller compared to the classical PID control strategy. In short, it can be concluded from experimental results that the excogitated control scheme can suppress the vibrations effectively and has a strong robustness to the flexible joint stiffness and the moment of inertia of the flexible load. The trajectory tracking performance of the designed controller is also very promising. Moreover, the presented controller is easy to be implemented, robust and adaptive in performance because the processing time is efficient with a better suppression in the vibration of the flexible joint manipulator.

In [11], investigations into the development of PD type Fuzzy Logic Control (FLC) with non-collocated Proportional Integral Derivative (PID) for trajectory tracking and vibration control of a flexible joint manipulator was presented. To study the effectiveness of the controllers, a PD type Fuzzy Logic Controller was developed for tip angular position control of a flexible joint manipulator. This is then extended to incorporate a non-collocated PID Controller for vibration reduction of the flexible joint system. Simulation results of the response of the flexible joint manipulator with the controllers were presented in time and frequency domains. The performances of the non-collocated PID control schemes were examined in terms of input tracking capability, level of vibration reduction and time response specifications.

The control schemes have been developed based on PD-type FLC and PD-type FLC with non-collocated PID control. The proposed control schemes were implemented and tested within the simulation environment of a single-link flexible joint manipulator. The performances of the control schemes were evaluated in terms of input tracking capability and vibration suppression at the resonance modes of the manipulator. Acceptable performance in input tracking and vibration control was achieved with proposed control strategies. A significant amount of vibration reduction at the joint of the manipulator was demonstrated with non-collocated PID. In terms of speed of responses, non-collocated PID results in a faster settling time response with high overshoot as compared to PD-type FLC.

In [17], improving the tracking performance of robots was focused on. Therefore, at the first step, there was the need to use the physical relations of the system to determine a model for the flexible joint robot manipulator. In his research, the Fuzzy Logic Self-

Tuning PID (FLST-PID) controller was introduced to keep the rotating angle of the link of FJR at the desired position. In the classic PID forms, the parameter values of the controller i.e. Kp, Ki, Kd were calculated in many various methods like Ziegler-Nichols and are constant. In FLST-PID, the parameter values computed by intelligent methods like fuzzy logic and they vary during the controlling process. For demonstrating the ability of the proposed controller, some classic controllers like PID, LQR and State Feedback will be designed for FJR and the response of the system with these controllers will be compared. Moreover, by considering some uncertainty on systems parameters, the comparisons were performed once again. Simulation results confirmed the claims and showed that the proposed controller has the best response for the system especially in uncertainty conditions.

2.3 Summary

This chapter summarizes the PID theory and a brief review of the past work carried out by researchers in the field ofthe PID control system. Dynamical progress is shown towards exhibiting the use of PID control to solve real-world problems. However, difficulties are counted in tuning the PID parametersdue to the complexity of the nonlinear equations involved, also its performance analysis needs to be evaluated and shown clearly via simulations. The next chapter will present the design of the PID controllers and the PID-based identified controller.

CHAPTER THREE

CONTROLLER DESIGN

3.1 Introduction

In this chapter, the model of the system will be described, followed by the PID design. The chapter also describes the use of least square estimation algorithm to design the identified controller.

3.2Flexible Manipulator Plant

The flexible manipulator mathematical models of both the hub angle and tip deflection in transfer function form are represented in equation 3.1 and equation 3.2.

$$G_{hub} = \frac{-1.492e(-13s^5) - 1014s^4 + 4553s^3 + 4.235e7s^2 + 2.865e7s + 1.785e10}{s^6 + 33.37s^5 + 9.726e4s^4 + 1.164e6s^3 + 7.257e8s^2} \tag{3.1}$$

$$G_{tip} = \frac{-3.553e(-14s^5) - 821s^4 - 3880s^3 - 4.315e7s^2}{s^6 - 33.37s^5 + 9.726e4s^4 + 1.164e6s^3 + 7.257e8s^2} \tag{3.2}$$

$$G_s = G_{hub} + G_{tip} \tag{3.3}$$

Parameters and the values of the flexible manipulator used during the course of the work are shown in table 3.1.

Table 3.1 Schematic diagram symbol

Parameters	Symbols	Values	Units
Young modulus	E	71×10^9	N/m^2
Mass density per unit volume	ρ	2710	Kg/m^3
Second moment of inertia	I	5.1924	m^4
Flexible link length	L	0.9	m
Width	w	19.008	mm
Thickness	t	3.2004	mm

The flexible manipulator plant is a state space model that was adopted with the following parameters as shown in figure 3.1.

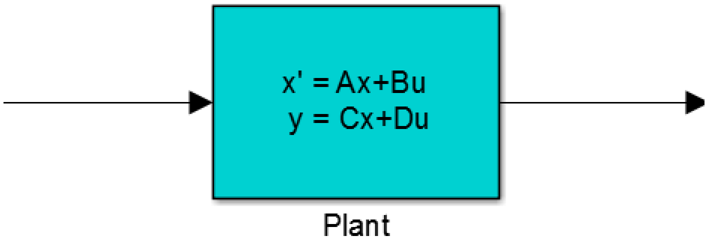

Figure 3.1 Diagram ofFlexible Manipulator in State Space Form

The model can also be represented in state space form as;

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (3.4)$$

$$y(t) = Cx(t) + Du(t) \quad (3.5)$$

After substituting the respective values in the state space equations, the values for A, B, C, and D were obtained as shown in equations 3.6, 3.7, 3.8 and 3.9 respectively.

Where:

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 58209 & -27441 & 0 & -33 & -6 \\ 0 & -38548 & 16329 & 0 & -27 & 4 \\ 0 & 93918 & -58611 & 0 & 16 & -6 \end{bmatrix} \quad (3.6)$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1.0136 \\ -0.8210 \\ 0.3041 \end{bmatrix} \quad (3.7)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.8}$$

$$D = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0] \tag{3.9}$$

3.3 PID Controller Design

In this section, design procedure of the PID controller is presented. The time-domain equation and general transfer function of PID controller are given as in equation 3.10[19] and equation 3.11[22].

$$U(t) = K_P \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d d \frac{e(t)}{dt} \right] \tag{3.10}$$

$$\mathrm{C}(S) = K_P + K_I \frac{1}{S} + K_D S \tag{3.11}$$

Where K_p, K_i and K_d are the proportional gain, integral gain and derivative gain respectively.

3.3.1 Auto Tuning Method

Auto tuning based on desired characteristics was used to design two PID controllers with PID1 having a slow response and no overshoot and PID2 having a fast response and overshoot. The following gains used for each PID controller are shown table 3.2.

Table 3.2 Auto tuning results

Controllers	K_p	K_i	K_d	N
PID1	0.02035	1.641e-05	5.60797	15.7976
PID2	607.741	187.149	109.278	5.5013

3.3.2 Obtaining Input/Output of the System

Matlab/Simulation was used to obtain input/output of the system using each PID controller. Two different input (step and bang-bang) signals were used for the system. The input/output characteristics of the PID controllers were obtained by running it to a workspace as shown in figure 3.2.

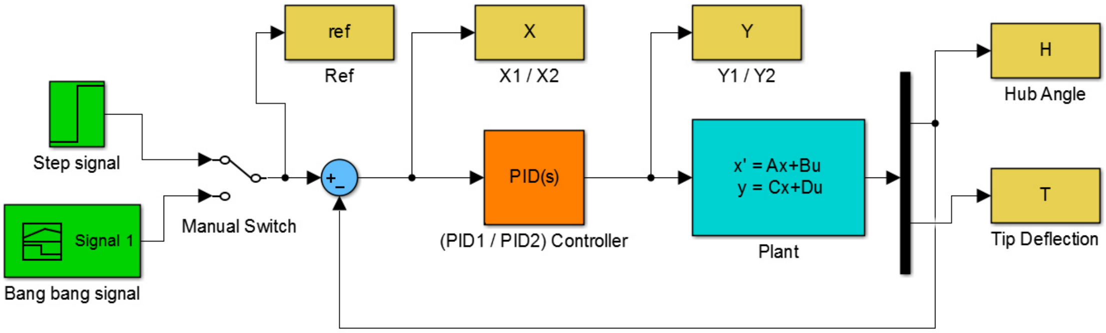

Figure 3.2 Simulink Block Diagram of PID1/PID2 Controller System

3.4PID-Based Identified Controller Design

A PID-based identified controller was designed from the combination of the desired characteristics of PID1 and PID2 controllers as shown in figure 3.3.

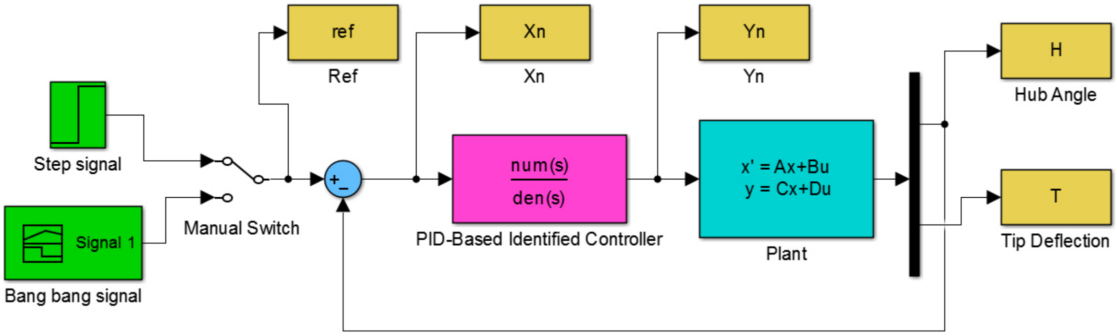

Figure 3.3 Simulink Block Diagram of Proposed Controller System

For PID1, the input/output characteristics are $\boldsymbol{X_1/Y_1}$

For PID2, the input/output characteristics are $\boldsymbol{X_2/Y_2}$

The proposed controller input/output characteristics are $\boldsymbol{X_n/Y_n}$

Where:

$$\boldsymbol{X_n} = [\boldsymbol{X_1}; \boldsymbol{X_2}] \tag{3.12}$$

$$\boldsymbol{Y_n} = [\boldsymbol{Y_1}; \boldsymbol{Y_2}] \tag{3.13}$$

Matlab/Simulation was used to obtain an identified controller from the combined desired output of the PID controllers. The transfer function of the PID-based identified controller are shown in equation 3.14 and equation 3.15

$$TF_{(z)} = \frac{637.9z^4 - 655.6z^3 + 24.18z^2 + 3.119z - 0.01609}{z^4 - 0.6631z^3 - 0.002088z^2 + 0.02963z + 0.0245} \tag{3.14}$$

$$TF_{(s)} = \frac{637.9s^4 + 22890s^3 + 536200s^2 + 4091000s + 797300}{s^4 + 37.09s^3 + 1029s^2 + 9320s + 3.2440} \tag{3.15}$$

3.5 Summary

This chapter presents the design procedures of the PID controllers and the PID-based identified controller. Auto tuning was used to achieve a desired output of the two PID controllers and Matlab/Simulation using system identification toolbox was used to obtain an identified controller from the combined desired output of the PID controllers. The controllers were simulated under various test signals to investigate their performances, the next chapter will discuss the results obtained and findings with detailed illustrations.

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, simulation results for hub angle and tip deflection control of flexible manipulator (FM) are presented and discussed. This is done with the creation of a proposed controller which is the PID-based identified controller that combines the characteristics of two PID controllers (PID1 and PID2) to get a better response. The results obtained for both PID controllers and the proposed controller were presented and compared under test signals of step response and bang-bang signal.

4.2 Step Response

A step signal was set as input to the system with PID1, PID2 and the Proposed Controller. PID1 controller has a slow response with no overshoot. PID2 has a fast response but with high overshoot. The proposed controller has small overshoot but with faster response than PID1 with no steady-state error. The output response of the system was taken and plotted. Figure 4.1 shows the Hub angle step response and table 4.1 summarizes the output values.

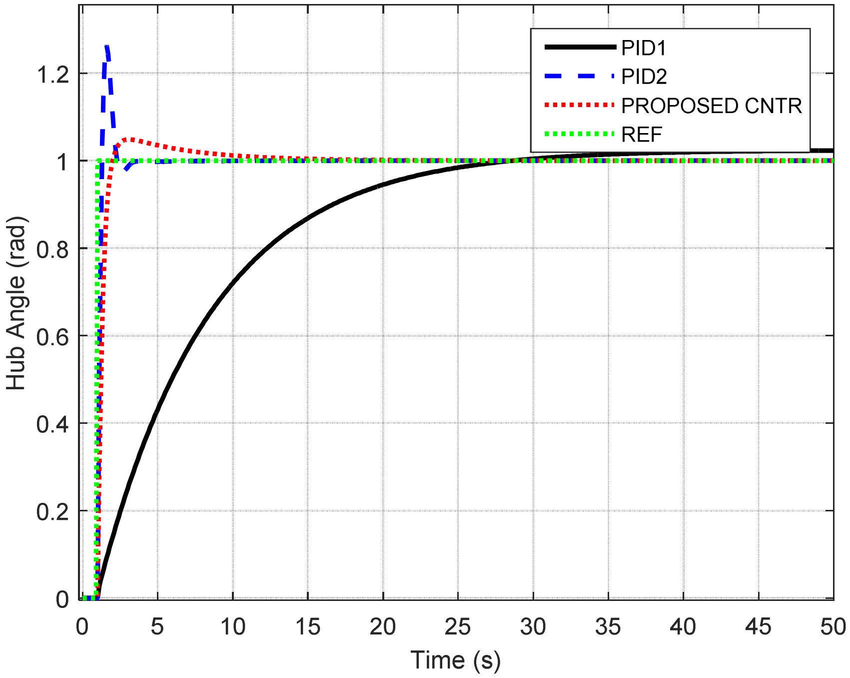

Figure 4.1Hub Angle Step Responses of the Controllers

Table 4.1 Summary of performance measures of FM hub angle step response

Controllers	**Settling time (secs)**	**Overshoot (rad)**	**Steady state error**
PID1	45	0	0.021
PID2	3	0.263	0
Proposed Controller	12	0.0488	0

For the tip deflection, a step signal was used as input to the controllers. PID1 has a small overshoot and undershoot and PID2 has a very high overshoot and undershoot. The proposed controller has a higher overshoot and undershoot than PID1 but less than PID2. PID1 settles faster than PID2 and the proposed controller. However, the proposed controller settles faster than PID2. Figure 4.2 shows the output response of the system and Table 4.2 summarizes the output values.

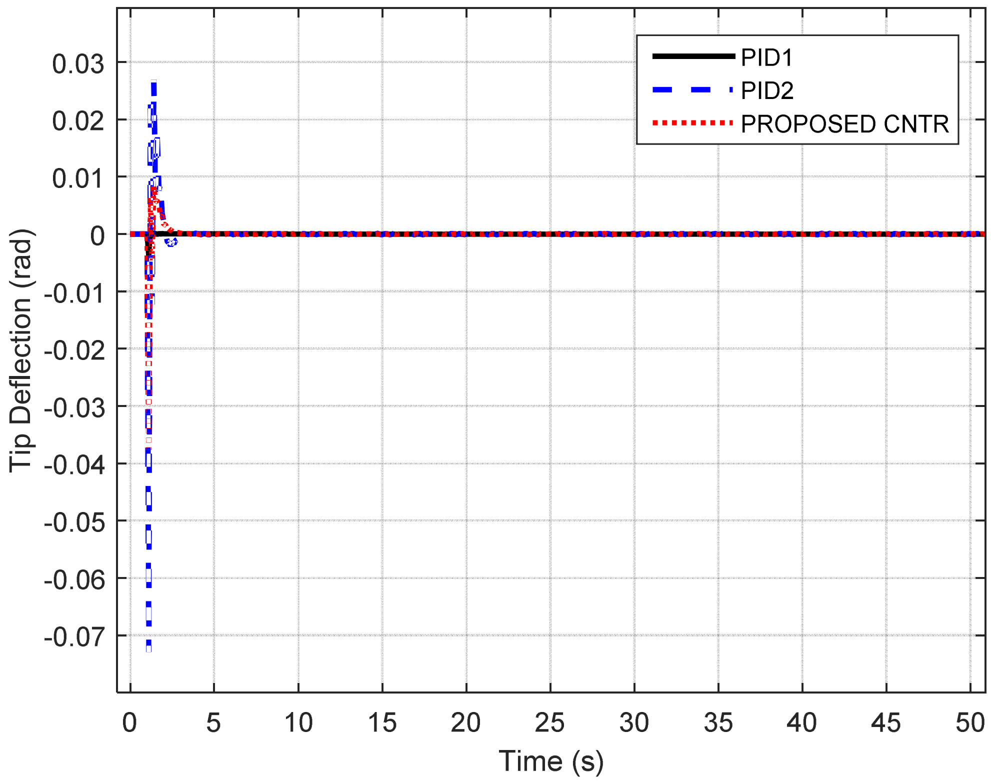

Figure 4.2Tip Deflection Step Responses of the Controllers

Table 4.2 Summary of Performance Measures of FM Tip Deflection Step Response

Controllers	**Settling time (secs)**	**Overshoot (rad)**	**Undershoot (rad)**	**Steady state error**
PID1	1.5	0.001	0.004	0
PID2	3	0.026	0.0725	0
Proposed Controller	2.5	0.007	0.037	0

For the control signal, a step signal was used as input to the controllers. PID1 has a small overshoot and no undershoot and PID2 has a very high overshoot and undershoot. The proposed controller has a lower overshoot than PID2 but higher than PID1. PID1 settles faster than PID2 and the proposed controller. However, the proposed controller settles faster than PID2. Figure 4.3 shows the output response of the system and Table 4.3 summarizes the output response values.

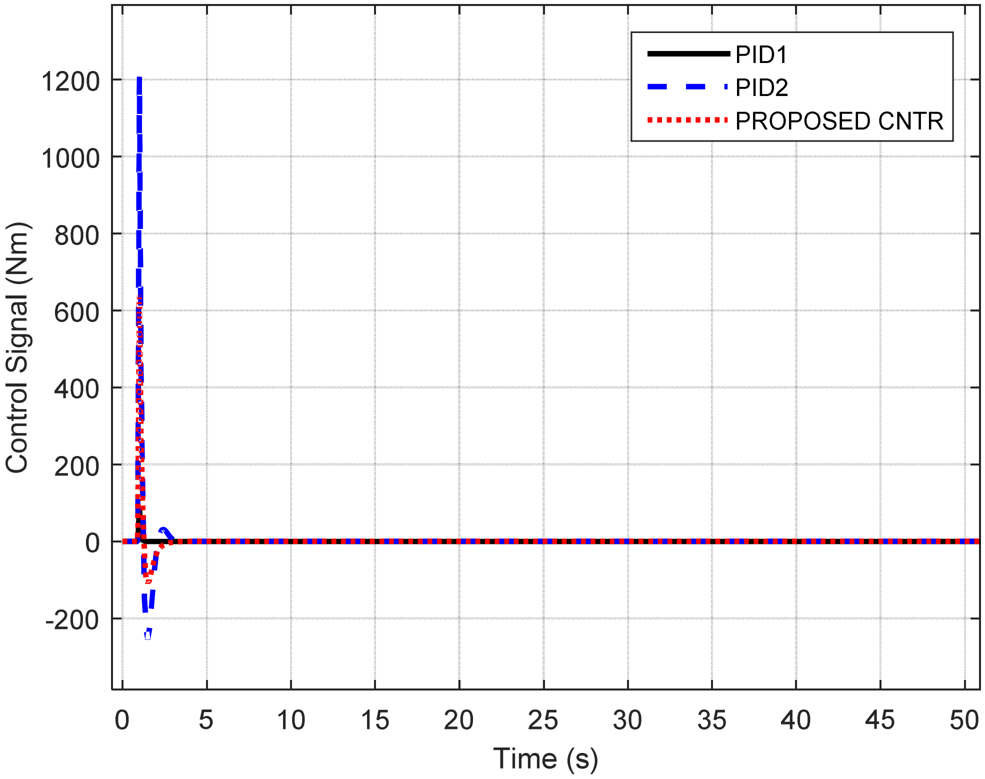

Figure 4.3Control signal step responses of the controllers

Table 4.3 Summary of performance measures of FM control signal step response

Controllers	Settling time (secs)	Overshoot (Nm)	Undershoot (Nm)	Steady state error
PID1	1.25	100	0	0
PID2	3	1200	220	0
Proposed Controller	2.5	620	100	0

4.3 Bang Bang Response

The idea of using a bang-bang signal is to observe the output responses with the controllers whether it tracks the input signal at different time intervals. This will enable us to know the robustness of the system. A bang-bang signal was set as an input to the system, the output behavior of the system was observed with the controllers and the combined responses were plotted versus time and compared accordingly.

Figure 4.4 shows the output signals of the hub angle output responses and table 4.4 shows the summary of the measured values.

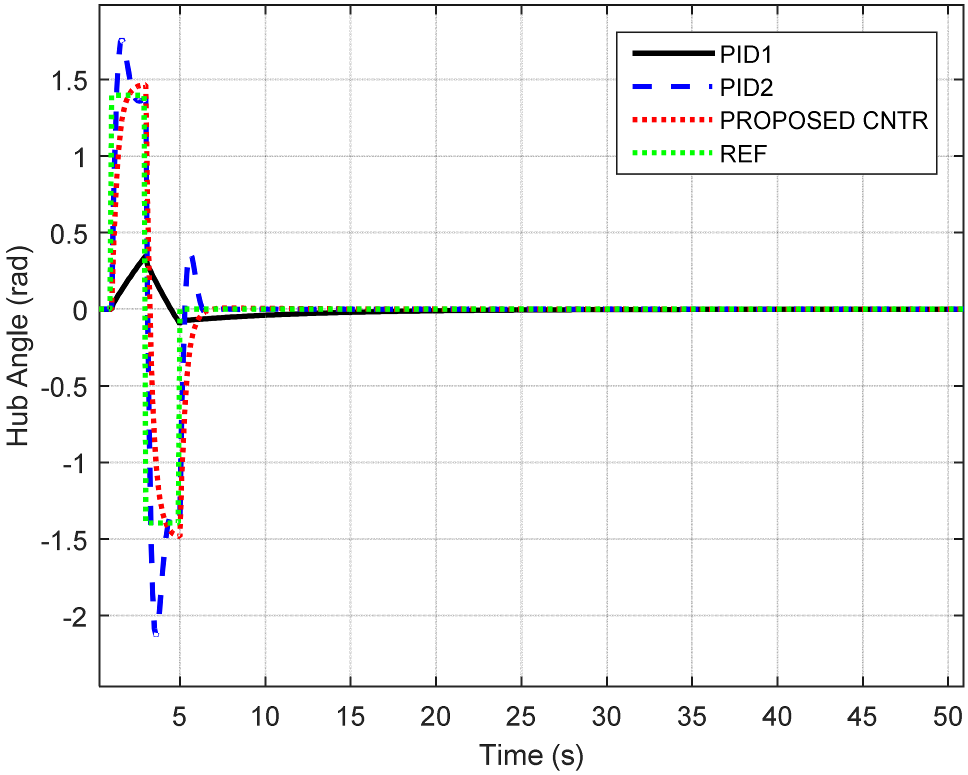

Figure 4.4 Hub Angle Bang Bang Signal Response

Table 4.4 Summary of Performance Measures of FM Hub Angle Bang Bang Response

	Max value(rad)	**Min. value(rad)**	**Steady state error**
Bang Bang signal	1.4	1.4	0
PID1	0.3	0.1	0
PID2	1.8	2.2	0
Proposed Controller	1.5	1.5	0

For tip deflection, a bang-bang signal was set as an input to the system, the output behavior of the system was observed with the controllers and the combined responses were plotted versus time and compared accordingly. PID1 has the smallest tip deflection. The proposed controller has a smaller tip deflection as compared to PID2. All the controllers have zero steady-state error. Figure 4.5 shows the output signals of the output responses and table 4.5 shows the summary of the measured values.

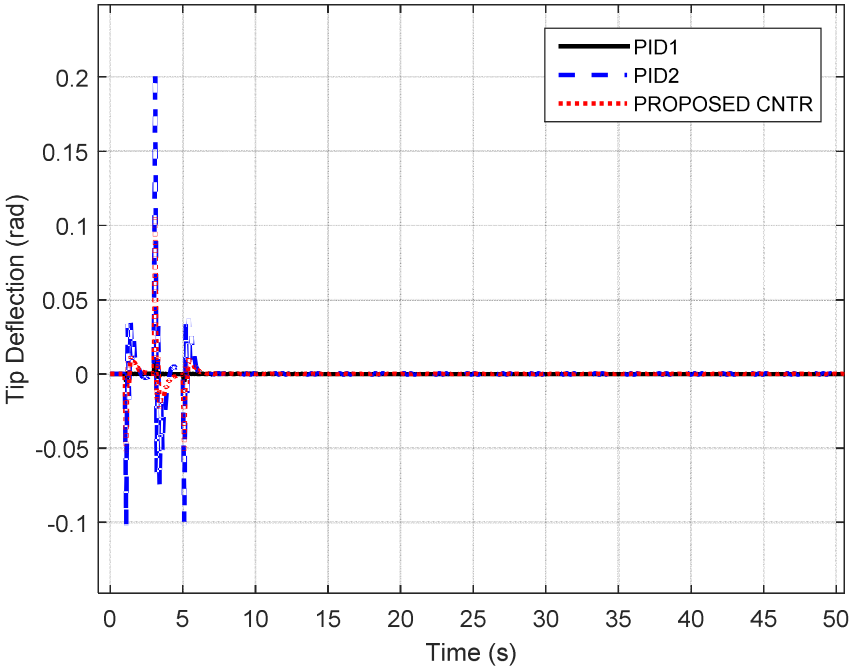

Figure 4.5Tip Deflection Bang BangSignal Response

Table 4.5 Summary of Performance Measures of FM Tip Deflection Bang Bang Response

Controller	**Max value (rad)**	**Min. value (rad)**	**Steady-state error**
PID1	0.01	0.01	0
PID2	0.2	0.1	0
Proposed Controller	0.1	0.05	0

For the control signal, a bang-bang signal was set as an input to the system, the output behavior of the system was observed with the controllers and the combined responses were plotted versus time and compared accordingly. Figure 4.6 shows the output signals of the output responses and table 4.6 shows the summary of the measured values

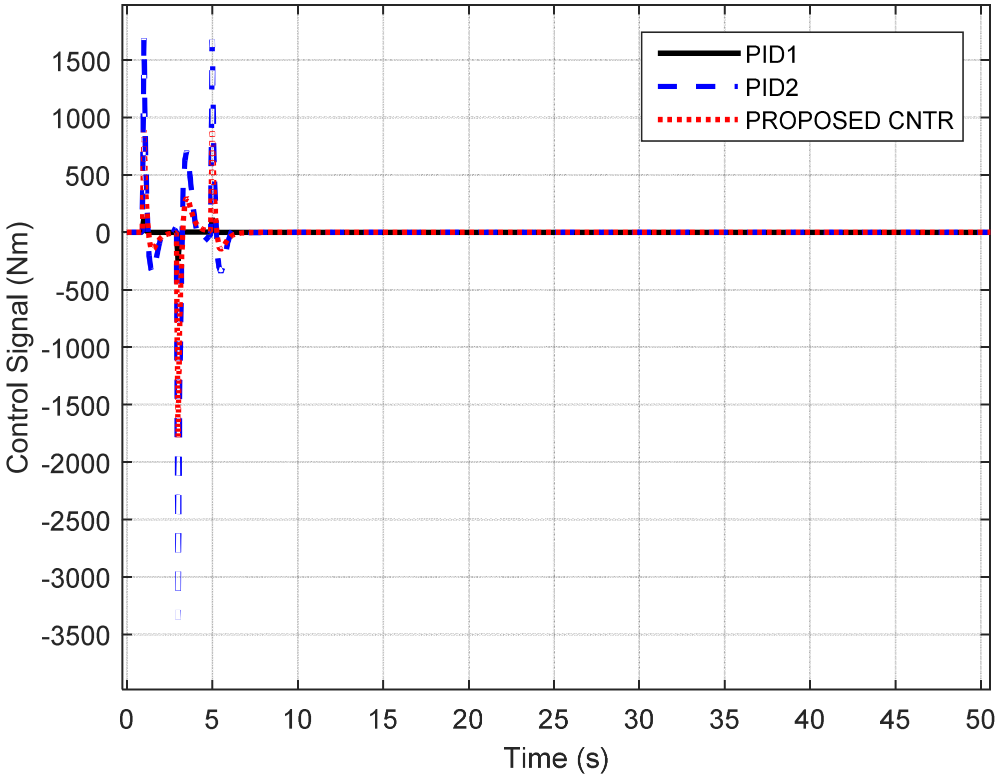

Figure 4.6 Control Signal Bang Bang Signal Response

Table 4.6 Summary of Performance Measures of FM Control Signal Bang Bang Response

Controller	**Max value (rad)**	**Min. value (rad)**	**Steady-state error**
PID1	100	200	0
PID2	1900	3400	0
Proposed Controller	800	1800	0

Looking at the plot from figure 4.4, it was observed that the proposed controller tracks the input bang-bang signal (reference signal) as compared to the output responses of PID1 and PID2. The bang-bang signal has a maximum value of 1.4 rad compared with the proposed controller value of 1.5 rad which is the closest of all the controllers where PID1 has 0.3 rad and PID2 has 1.8 rad maximum value. Furthermore, the minimum value of the bang-bang signal is 1.4 rad compared with the proposed controller minimum value of 1.5 rad which is also the closest value of all the controllers where PID1 has 0.1 rad and PID2 has 2.2 rad minimum value. This indicates that the proposed controller has a better precision and better robustness control than PID1 and PID2.

4.4 Summary

Having seen the results obtained, starting with the step signal response, the hub angle settling time for PID1 decreased by 73% compared to the proposed controller settling time. However, the settling time for PID2 increased by 300%. There was a percentage decrease of PID2 overshoot by 81% to the proposed overshoot. Tip deflection settling time for PID2 decreased by 17% compared to the proposed controller. However, settling time for PID1 increased by 50%. PID2 overshoot decreased by 73% but with an increase of 86% for PID1. The control signal for PID2 decreased by 48% but with an increase of 84% for PID1 when compared with the proposed controller. The results shows that PID1 has the fastest response time than the remaining controllers and the proposed (PID-based identified) controller has the highest precison value than the PID controllers.

Considering results for the bang-bang signal response, the proposed controller hub angle maximum value has a slight increase of 7% with the reference bang-bang signal compared to PID1 with a decrease of 79% and PID2 with an increase of 29%. The minimum value for the proposed controller hub angle increase by 7% with the reference signal with a decrease of 93% for PID1 and an increase of 57% for PID2. The tip deflection maximum value for PID2 decreased by 50% compared to the proposed controller. However, the maximum value for PID1 increased by 900%. PID2 minimum value decrease by 50% but with an increase of 406% for PID1.Control signal bang response for PID2 decrease by 58% but with an increase of 700% for PID1 when compared with the proposed controller. The results shows that PID1 has the best tip deflection response than the remaining controllers and the proposed (PID-based identified) controller has the highest robustness to track different time intervals than the PID controllers.

CHAPTER FIVE

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

5.1 Conclusion

The basic aim of this thesis is todevelop an identified model controller for a single link flexible manipulator. In order to realize this aim, a reasonable survey on different PID controller systems gives rise to a literature review presented in chapter two. The mathematical model of the Flexible Manipulator plant was adopted as presented in chapter three. The proposed controllers designed were set to provide a precise hub angle and tip deflection. The controlled system as examined under various test signals showed that better performance was achieved using the proposed controller because of its robustness to track different input signals to the system for the hub angle with only a slight tip deflection better than PID2, with the help of MATLAB/SIMULINKenvironment simulation results were obtained and presented accordingly.

5.2 Contribution

The research contribution are highlighted below

- The hub angle step response for the PID-based identified controller has a faster settling time than PID1 by 73%.
- The hub angle step response for the identified controller has a better overshoot than PID2 by 81%.
- The tip deflection step response for the identified controller has a better settling time than PID2 by 17%.
- the hub angle bang-bang response of the identified controller has the best maximum value with only a slight increase of 7% with the reference bang-bang

signal as compared to PID1 with a decrease of 79% and PID2 with an increase of 29%.

5.3 Recommendation

From the design, it can be seen that the precision of the system and the performance of the controller depends on the values of the gains. For future work, it is recommended that there is the need for further investigation of PID controller which will bring about simpler methods in tuning its parameters as need of precision are demanded especially in automatic control aspect.

REFERENCES

[1] Auwalu M., Amiru A., Mohamed Z., Zainal A., Akmeliawati R., “Stability Analysis and Vibration Control of a Class of Negative Imaginary Systems”, Faculty of Electrical Engineering, UTM Johor Bahru, Malaysia, pp. 77-83, 2015.

[2] Pereira E., “Integral Resonant Control for Vibration Damping and Precise Tip-Positioning of a Single-Link Flexible Manipulator”, Mechatronics, IEEE/ASME Transactions, vol. 16,pp. 232-240, 2011.

[3] Mannani, A., H. A. Talebi, “Fuzzy lyapunov synthesis-based controller for a flexible manipulator”, IEEE Conference on Control Applications, Toronto, Canada, pp. 607-611, 2005

[4] Feliu, V., “Robust tip trajectory tracking of a very lightweight single-link flexible arm in presence of large payload changes”, Mechatronics, vol. 22, pp. 594-613, 2012.

[5] Jun-qiang L., Yan-ding W., Yi-ling Y., Feng-ran X., “Hybrid PD and effective multi-mode positive position feedback control for slewing and vibration suppression of a smart flexible manipulator”, College of Mechanical Engineering and Mechanics, Ningbo University, Ningbo, People’s Republic of China, pp. 1-14, 2015.

[6] H. Tjahyadi, F. He, K. Sammut, “Multi-Mode vibration control of a flexible cantilever beam using adaptive resonant control”, Smart materials and structures, vol.15 pp. 270-278, 2006.

[7] Jim-Xin Xu, Wen-Jun Cao, “Active Vibration Manipulator Control of a Single-Link Flexible by Pole-Placement Approach”, Proceedings of the 38" Conference on Decision & Control Phoenix, Arizona USA, pp. 3888-3893, December, 1999.

[8] Subhash Chandra Saini, Yagvalkya Sharma, Manisha Bhandari, UditSatija, “Comparison of Pole Placement and LQR Applied to Single Link Flexible

Manipulator", International Conference on Communication Systems and Network Technologies, Kota India, pp. 843-847, 2012.

[9] Mahmood, I.A., B. Bhikkaji, S.O.R. Moheimani, "Vibration and Position Control of a Flexible Manipulator in Information, Decision and Control", School of Electrical Engineering and Computer Science, The University of Newcastle Callaghan, NSW Australia, pp. 260-265, 2007.

[10] Ahmad, M.A., "Vibration control of flexible joint manipulator using input shaping with PD-type Fuzzy Logic Control in Industrial Electronics", ISIE IEEE International Symposium, Seoul Olympic Parktel, Seoul, Korea, pp. 1184-1189,2009.

[11]. M. A. Ahmad, M. H. Suid, M. S. Ramli, M. A. Zawawi, R. M. T. Raja Ismail, "PD Fuzzy Logic with non-collocated PID approach for vibration control of flexible joint manipulator", IEEE 6th International Colloquium on Signal Processing & its Applications, 2010

[12] Q. P. Ha, H. Trinh, J.G Zhu and H. T. Nguyen, "Dynamic output feedback control of single-link flexible manipulators", Australian comference on Robotics and Automation, Sydney, pp. 7-12, 14-15 November, 2001.

[13] Ismail H. Akyuz, ErsinYolacan, H. MetinErtunc, ZaferBingul, "PID and state feedback control of a single-link flexible joint robot manipulator", Department of Mechatronics Engineering, Kocaeli University, Kocaeli, Turkey, 2011.

[14] B.A. Md Zain, M. O. Tokhi,, S.F. Toha, "PID-based Control of a Single-Link Flexible Manipulator in Vertical Motion with Genetic Optimisation", Department of Automatic Control and Systems Engineering, University of Sheffield, United Kingdom, pp. 355-360, 2009.

[15] M. A. Ahmad, "Vibration and Input Tracking Control of Flexible Manipulator using LQR with Non-collocated PID controller", Faculty of Electrical and Electronics Engineering, University Malaysia Pahang (UMP), pp. 40-45, 2008.

[16] Hazrat Bilal, Wei Yao, Yu Guo, Yifei Wu, Jian Guo, "Experimental validation of fuzzy PID control of flexible joint system in presence of uncertainties", IEEE 36th Chinese Control Conference (CCC), Dalian China, pp. 4192-4197, 2017.

[17] Ali Dehghani, Hamed Khodadadi, "Fuzzy Logic Self-Tuning PID control for a single-link flexible joint robot manipulator in the presence of uncertainty", IEEE 15th International Conference on Control, Automation and Systems (ICCAS), Busan Korea, pp. 186-191, 2014.

[18] Pota, H.R., S.O.R. Moheimani, and M. Smith, "Resonant controllers for flexible structures. in Decision and Control", Proceedings of the 38th IEEE Conference, Canberra Australia, pp. 631-636, 1999.

[19] Jnifene, A., W. Andrews, "Experimental study on active vibration control of a single-link flexible manipulator using tools of fuzzy logic and neural networks", Instrumentation and Measurement, IEEE Transactions, Ottawa Canada, vol. 54 pp. 1200-1208, 2005.

[20] Feliu V., Kuldip S., Benjamin B., "Adaptive control of a single-link flexible manipulator", IEEE Conference on Robotics and Automation, Carnegie-MelIon University, Pittsburgh, pp. 29-33, 1990.

[21] G. Venkata Narayana and P. Ramesh, "Modelling and Control of Single Link Manipulators for Flexible Operation by using Linearization Techniques", International Journal of Current Engineering and Technology ISSN 2277 – 4106, Vol.3, No.2 June, 2013.

[22] M. A. Ahmad, M.H. Suid, M. S. Ramli, M. A. Zawawi and R. M. T. Raja Ismail, "PD Fuzzy Logic with Non-collocated PID Approach for Vibration Control of Flexible Joint Manipulator" Faculty of Electrical Engineering, Universiti Malaysia Pahang, 26600, Pekan Malaysia, pp. 53-57, 2010.

[23] M.O.Tokhi, Z. Mohamed and M.H. Shaheed, "Dynamic characterisation of a flexible manipulator system. in Robotica", Department of Automatic Control and

Systems Engineering, The University of Sheffield, United Kingdom, volume 19, 571-580, 2013.

[24] J. Katende and M. Mustapha, "Neural Network Control of a Laboratory Magnetic Levitator in Integrated Models for Information", Communication Systems and Networks: Design and Development, pp. 361-374, 2013.

[25] S. A. Billings, H. B. Jamaluddin, S. Chen, "Properties of neural networks with applications to modelling nonlinear systems", Department of Automatic Control and Systems Engineering , University of Sheffield , Mappin Street, Sheffield, SI, 3JD, U.K, vol. 55, pp. 193-224, 1992.

[26] Auwalu M. Abdullahi, Z. Mohamed, Mustapha Muhammad, A. A. Bature, "Vibration Control Comparison Of A Single Link Flexible Manipulator Between Fuzzy Logic Control And Pole Placement Control", International Journal Of Scientific & Technology Research, Department of Mechatronics Engineering, Bayero University, Kano, Nigeria, vol. 2, pp. 236-241, 2013.

[27] Ahmad M.A., "Vibration control of flexible joint manipulator using input shaping with PD-type Fuzzy Logic Control",IEEE International Symposium on Industrial Electronics (ISlE 2009) Seoul Olympic Parktel, Seoul, Korea, pp. 1184-1189, 2009.

[28] Feliu, V., Castillo, F. J., Ramos, F., & Somolinos, J. A., "Robust tip trajectory tracking of a very lightweight single-link flexible arm in presence of large payload changes", School of Industrial Engineering, University. of Castilla-La Mancha, Ciudad Real Spain, pp. 594-613, 2012.