POSITION AND ANTI-SWAY CONTROL FOR A GANTRY CRANE SYSTEM USING FUZZY-TUNED PID CONTROLLER

KANTHA RAO A/L SIMANJALAM

A project report submitted in partial fulfillment

of the requirement for the award of the degree of

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To my beloved family members,

mum Genga Devi, dad Simanjalam,

brother Rama Rao, and sisters Surria Kantha and Suriya Devi

who have given me unlimited support for me to forward and complete this work.

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ABSTRACT

Crane system is widely used to transport payload from one point to another point. When input signal is applied to a crane system, the trolley will start to accelerate whilst causing swing of payload. The ability to successfully transfer a payload by fulfilling the requirements is highly dependent on operator skill, where a simple mistake can lead to accident and fatality. The objective of this project is to come up with a control system design to automate the crane system in order to achieve its operating goals. The modeling of the control system for the purpose of this project is derived based on Euler-Lagrange formulation, and a gantry crane incorporating a payload is considered. The controller applied was fuzzy-tuned PID. Fuzzy logic has been chosen because of its ability to mimic human behavior accurately. On top of that, employing simple structure of PID controller by utilizing fuzzy system as gain tuners is able to improve the robustness of the crane system to cope with parameter variations. The end result is obtained through Matlab Simulink and the effectiveness of the controller was investigated in terms of time response, percentage of overshoot, payload sway and also robustness.

ABSTRAK

Sistem kren digunakan dengan meluasnya untuk tujuan memindahkan bahan dari satu tempat ke tempat yang lain. Apabila daya dikenakan ke atas system kren,troli akan memecut ke hadapan sambil menyebabkan hayunan terhadap beban yang tergantung. Memindahkan beban dari satu destinasi ke destinasi yang lain dalam masa yang paling singkat tanpa menyebabkan hayunan memerlukan operator yang mempunyai kemahiran tinggi, kerana kesilapan yang kecil boleh menyebabkan kemalangan ataupun lebih teruk lagi, kematian. Objektif projek ini adalah untuk mereka satu sistem kawalan automatik yang dapat beroperasi secara selamat. Permodalan sistem untuk projek ini diperolehi menggunakan kaedah formulasi Euler-Lagrange, dan sistem kren yang mempunyai beban dipertimbangkan sepanjang projek dijalankan. Sistem kawalan yang digunakan untuk projek ini ialah PID boleh kawal menggunakan *Fuzzy Logic*. Fuzzy Logic dipilih kerana keupaayannya untuk memimik kelakuan manusia. Selain itu menggunakan PID yang mempunyai rekabentuk yang ringkas, ditambah lagi *fuzzy logic* yang digunakan untuk mengawal gandaan parameter PID dapat meembolehkan sistem kawalan gabungan tersebut dapat mengekalkan respons walaupun parameter seperti berat beban dan panjang kabel diubah. Simulasi dijalankan menggunakan perisian Matlab Simulink, manakala pencapaian sistem kawalan diuji dari segi masa tindakbalas, kadar pengurangan getaran, dan juga kebolehan untuk membawa beban.

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LIST OF SYMBOLS AND ABBREVIATION

x_1	-	Cart final position
$\dot{x}_1$	-	Cart Velocity
$\ddot{x}_1$	-	Cart Acceleration
m_C	-	Mass of cart
m_L	-	Mass of load
θ	-	Angle between bar and vertical axis (Sway angle)
$\dot{\theta}$	-	Angular velocity
$\ddot{\theta}$	-	Angular Acceleration
l	-	Length of bar
PD	-	Proportional Derivative Controller
PID	-	Proportional-Integral-Derivative Controller
FPID	-	Fuzzy-tuned PID
FPID + FPD	-	Fuzzy-tuned PID plus Fuzzy-tuned PD
k_P	-	Proportional gain
k_I	-	Integral gain
k_D	-	Derivative gain
ITAE	-	Integral of Time Absolute Error

CHAPTER 1

INTRODUCTION

1.1 CRANE: OVERVIEW

Crane is a machine or device used by human to help humans to move loads, or better known as payload, from one point to another. A crane is typically equipped with a hoist or wire rope drum, wire ropes or chains and sheaves that can be used to lift or lower the load or move the load horizontally. The hoist functions as a simple machine which helps human to move loads beyond the capability of a human.

First crane were apparently designed by the Ancient Greeks [1] since 900BC. The early version of crane was operated using human or animal power such as donkey. The Ancient Greeks were believed to have utilised these cranes in erection of tall structures for building construction.

In our modern world, the need to move load, such as equipment, tools etc. from one place to another, be it far or near has become very crucial. The load to be moved is usually heavy, large and hazardous, which cannot be handled manually by workers. For instance, shipyard and heavy workshop depends on crane to move materials or equipment from one point to another.

There are many types of crane that has been used for these purposes, such as tower crane, overhead crane, boom crane, gantry crane and others. Figures 1.1 and 1.2 show examples of overhead crane and gantry crane, respectively.

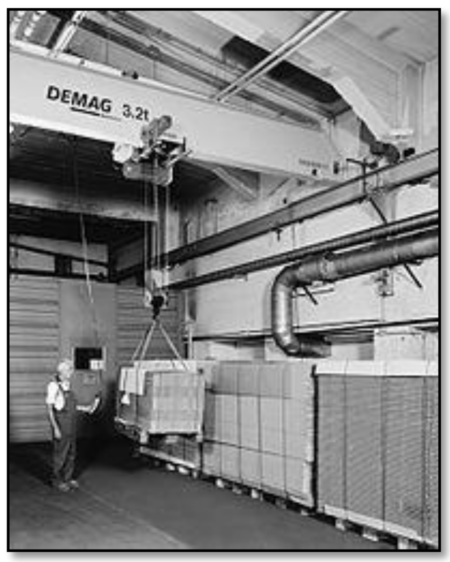


Figure 1.1 Overhead Crane

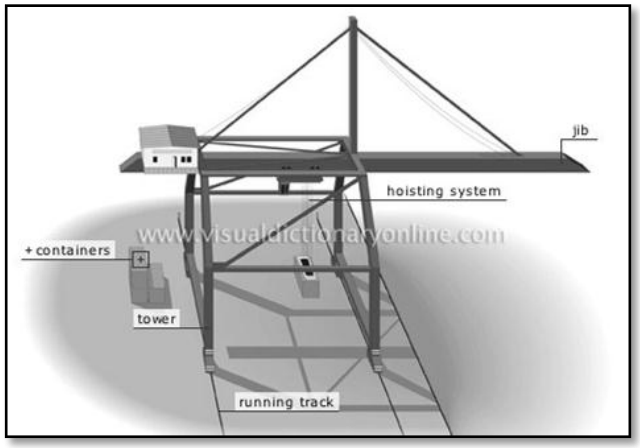


Figure 1.2 Gantry Crane

As mentioned earlier, a crane consists of a hoisting mechanism (usually a hoisting line together with a hook) and a support mechanism. A cable with the load hanged on the hook is suspended from a point on the support mechanism. The support mechanism, also known as cart, will move the hanged load around the crane workspace, while the hoisting mechanism will lifts and lowers the load to prevent the obstacles in the path and locate the load at the desired location.

Cranes exist in a wide variety of forms, each designed to suit to a specific use. The sizes range from a small jib cranes used inside workshops to the tall tower cranes used for constructing high-rise buildings, and the large floating cranes used to build oil rigs and salvage sunken ships.

There are many type of crane, which depends on their application: automatic crane, cab-operated crane, cantilever gantry crane, floor-operated crane, gantry crane, jib crane, mobile crane, overhead traveling crane, power-operated crane, pulpit-operated crane, remote-operated crane, semi gantry crane, wall-mounted crane and wall-mounted jib crane. For the purpose of this study, control analysis will be focused on gantry.

1.2 GANTRY CRANE

Gantry crane is a type of crane that lifts objects by a hoist which is fitted in a hoist trolley and can move horizontally on a rail or pair of rails fitted under a beam. The gantry crane is limited to a 2D movement which is horizontal and vertical movement. For the purpose of this project, we will limit the movement of gantry crane to horizontal only.

Gantry crane is similar to an overhead crane, except that the bridge for carrying the trolley or trolleys is rigidly supported on two or more legs running on fixed rails or other runway. To perform gantry operation, the crane operator will seat inside the cart, and move the cart with the load hanged with it so that the load can be moved to the desired location. A real crane may allow a cart movement of 80 to 90 meters [2], determined by the desired load location.

1.3 PROBLEM STATEMENT

While operating the crane, the most important factor is to ensure the operating safety. A simple mistake can lead to non-fatal or even fatal injury. Hence, the crane must be operated in safe operating manner and follow the proper procedures. According to one study done by Ray Rooth and Ken Fry [3] under Division of Occupational Safety and Health to analyze crane accidents from 1997-1999, it was found that over the three-year period, at least one crane accident has occurred in each month of the three year period. The cause of the accidents obtained through the study is shown in Table 1.1.

Table 1.1 Most Frequent Causes : All Crane Types (N-158) and Mobile Cranes (N-115)

	All Crane Types	Mobile Cranes
Instability	67	49

Unsecured Load	34	6
Load Capacity Exceeded	0	29
Ground not level/too soft	0	4
Lack of Communication	32	24
Electrical Contact	13	10
Miscellaneous in 14 Categories	46	32

From the table above, it can be seen clearly that most of the accidents were caused by unsecured load and load capacity exceeded. On other example, an accident occurred on 28th April 1993, where a crane became unbalanced while the boom was being lowered. On other occasion two days later, on 30th April 1993, while load was being loaded, the excessive weight of the load caused the crane to tip forward [4]. From these incidents, guidelines have been suggested to ensure safety while using the cranes. Some of the guidelines are:

i. the weight of load must be checked.
ii. crane operations should be supervised by qualified personnel.
iii. crane operators must be familiar with their equipment.
iv. crane operators must be trained and qualified to operate their equipment.

Despite guidelines have been sketched in order to prevent the accident, other factors also must be taken into consideration so that the probability of accident to occur is small or reduced to an acceptable value. In terms of control system, the cause of accidents such as unsecured load and excessive load can be linked to big sway angle. Thus it is important for us to control the sway angle in order to ensure faster operation while maintaining safety issue.

1.4 SIGNIFICANCE OF STUDY

Many researchers have given a lot of efforts in developing control algorithms and designing controllers that can be used and realized in nature for crane control purpose. This includes works related on reducing load vibration, especially in crane, where many types of controllers have been designed to control the load swing.

Since this is relatively simple and well defined problem in terms of dynamics and control, there has not been an exact solution that guarantees complete success in a finite time. Most of the crane controllers that have been developed until now have been far from satisfactory. Thus this study is expected to yield a complete control system which will be able to be implemented in reality in order to achieve a satisfying output.

In term of controller available in market, most of the controllers utilize PID controllers as mean of controlling. Problem with PID controller is that it has to be tuned every time the load or length of crane rod is changed. This is because PID controller does not have robust property. Thus a controller which can be robust to parameter variation is essential.

1.5 OBJECTIVES

The objectives of this study can be divided as the following:

- To obtain dynamic model of a gantry crane to be used for simulation study and controller development throughout the study.
- To develop a PID controller for control of position and sway of the crane system.
- To establish a fuzzy-tuned PID controller for control of a gantry crane with parameter variations in the crane system.

1.6 SCOPE OF STUDY

There will be several limitations or restriction in accomplishing this study. First of all the study on crane control response will be limited to gantry crane variant. The study of the crane will also be limited to a 2-dimensional movement.

Apart from that, due to time constraint in completing this project, the obtained dynamic model will be verified with previously published results. Two of the many outputs of the gantry crane which will be considered for this study will be the position of the cart/trolley and also the sway of payload.

The simulation of the designed controller will be obtained using Matlab Simulink software where the load oscillation and final position of the cart can be observed via built-in scope.

CHAPTER 2

LITERATURE REVIEW

2.1 DEFINITION OF GANTRY CRANE

Gantry cranes are the kind of crane that lifts items by a hoist [5]. The hoist is placed in a trolley that can move in a horizontal direction on rails fitted under a beam. The gantry crane is supported by uprights, with wheels fitted to facilitate the crane traverse. Gantry cranes are especially suitable for the lifting of heavy objects. Extremely large gantry cranes are being used for shipbuilding, where the crane can move along the ship with heavy loads.

There are also gantry cranes which are fitted with rubber tires allowing the movement of the crane in automobile or other workshops. These are called workstation gantry cranes and are used for lifting and transportation of small objects in a factory. Some of these cranes include a track, an I-beam, or some other extruded form as the path of movement for gantry crane. Most of the workstation gantry cranes are designed to be immobile in a loaded condition, and movable when not loaded. The crane lifting capacities are determined by the crane parts fitted.

Gantry cranes are usually used in the rail yards and shipping yards for the loading or unloading of loads, and large containers from trailers as shown in Figure 2.1 below. Gantry cranes are also especially useful in industrial units, where they can move objects on the factory floor while the product is gradually being assembled. There are several processes on an assembly line that require frequent movement of the parts and assemblies. Manual movement will not only be difficult, it will not be fast compared to the mobility of a gantry crane.

Figure 2.1 Gantry Crane Used For Unloading of Loads at Shipping Yard

2.2 HISTORY OF GANTRY CRANE

The first crane company in the world is Germany Ludwig Stuckenholz which is now known as Demag Cranes & Components GmbH [6]. The first mass-production of the company was steam-powered crane as illustrated in Figure 2.2.

Figure 2.2 Steam Crane Using a Line Shaft for Power Produced by Stuckenholz AG, Wetter am der Ruhr, Germany

Gantry cranes using built-up style hoists are frequently used in modern systems. These built up hoists are used for heavy-duty applications such as steel coil handling and for users desiring long life and better durability.

Just as how the usage of gantry crane grows rapidly, accidents occurring due to human error and lack of controllability are also unavoidable. As discussed in earlier chapter, most of these accidents occur due to uncontrolled load and transfer speed of the payloads. When a heavy load is being transferred, it is very dangerous if the load is transferred at high speed because the load will tend to sway. This can lead to the whole crane system be unstable or the payload might swing and hit nearby structure causing damage and injury to human being as well.

2.3 MODELING OF GANTRY CRANE

To ensure that the developed control algorithm is appropriate with the focused problem, one aspect that cannot be ignored is the model of gantry crane itself. Some researchers take the characteristic of pendulum as their model to derive dynamic equation that represents the gantry crane. This step is very crucial in order to ensure that analysis done using simulation will reflect actual system.. Therefore, a lot of consideration and factors have been taken into account while developing the mathematical model that represents an actual system.

Mathematical modeling can be done using various methods. One method is using Euler-Lagrange formulation. While deriving the model, a lot of assumption also has to be made. For example, some study was done using model which includes motor in the system, whereas some other study does not include motor in the system. Apart from that, mathematical model of a gantry crane usually appear in non-linear form. Thus, linearization has to be made by to eliminate the non-linear variable.

2.4 CONTROL OF GANTRY CRANE

Basically there are so many methods which can be used to control the performance of gantry crane. Among others are output-delayed feedback controls, fuzzy-tuned PID controller, and low pass filter technique. A few techniques are explained below.

In term of control, one of the ideas suggested for implementation was by team of Dey.R, Sinha.N, Chaubey.P and S. Ghosh and G. Ray who recommended use of output-delayed feedback control (ODFC) technique for active sway control of single pendulum gantry crane [7]. Using ODFC method, under-damped system was controlled by producing a signal which is derived from the position sensor which is then combined with the delayed output signal from the same sensor and fed back to the system. This design, however, requires prior knowledge of the controller gain for which the time-delay is treated as design parameter.

On the other hand, Solihin.MA, Wahyudi and Abdulgani proposed the development of soft sensor to achieve sensorless automatic gantry crane using RBF

Neural Networks [8]. This method was introduced to eliminate the use of real sensor. Instead, a sensor measuring armature current of DC motor driving the cart is used to provide dynamic information of the soft sensor.

Solihin.MA and Wahyudi suggested the use of fuzzy-tuned PID controller for automatic gantry crane [9]. Their goal was to engage a simple a simple structure of PID controller by utilizing fuzzy logic system as gain tuners. That means the gain of the PID controller will be determined by means of fuzzy inference system. This method was proposed as a way to gain advantage of robustness to parameters variations for anti-sway gantry crane control. This will enable the system to satisfy control performance without being affected by parameter change (eg. hoisting cable length, payload mass).

For the purpose of this study, control design will be focused on fuzzy-tuned PID. This is because of all techniques, fuzzy-tuned PID provides better robustness to variation of parameter values. This will enable the crane system to satisfy control performance for varying value of crane parameters, which in other word means more flexibility.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

The flow of work methodology can be summarized and will be executed in two parts, namely Final Year Project Part 1(FYP 1) and Final Year Project Part 2(FYP2).

3.2 RESEARCH PROCEDURE

First step in for this project to understand all the necessary theories necessary in completing the project. Then next step would be to obtain the dynamic mathematical model of a crane system using Newton’s Law of Motion method. Next, the mathematical model will be verified by simulating and comparing with previous works.

FYP 2 will be started by implementing Genetic Algorithm code to obtain most optimized PID parameters for gantry crane. After that, fuzzy inference system will be designed to be used as fuzzy-tuner for PID controller. The response of fuzzy-tuned PID controller will be shown using Matlab Simulink.

Lastly, the fuzzy rules base will be tuned to obtain the most optimized and stable system. After that, analysis and report writing will be completed based on obtained data. The complete process flow is summarized in Figure 3.1 below.

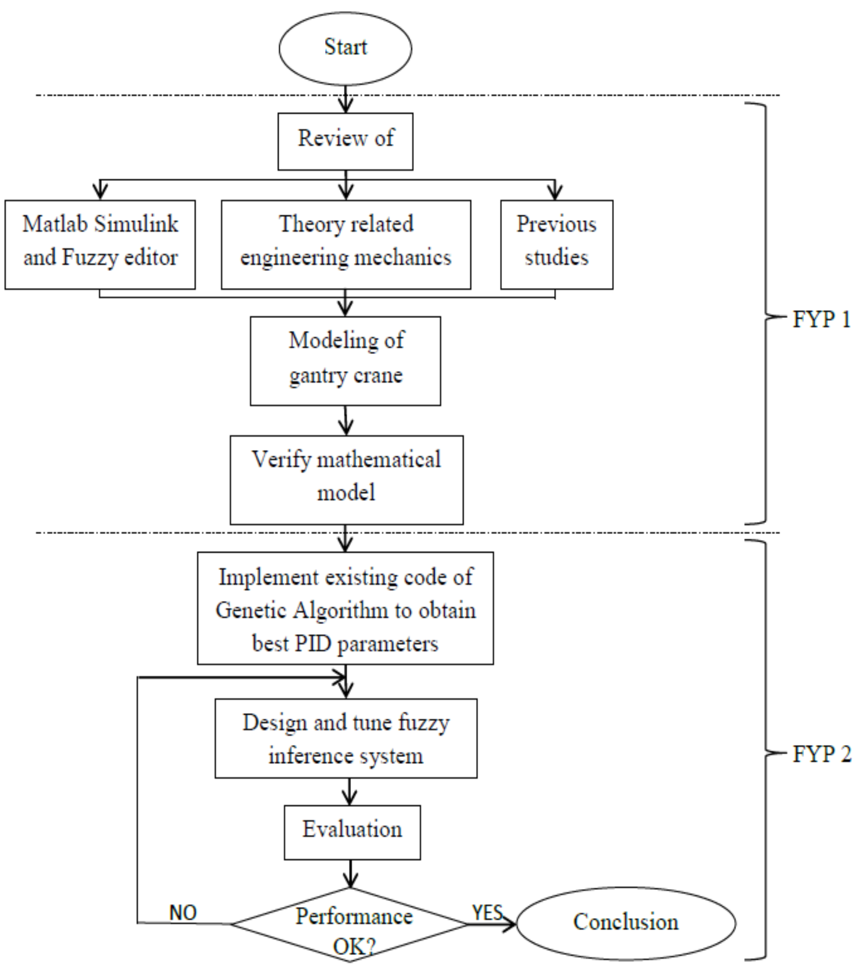


Figure 3.1 Project Flow Summaries

3.3 FUZZY-TUNED PID CONTROL DESIGN

A PID controller can be tuned to produce the best or optimized result. However the PID controller itself is not robust to parameter variation. The parameter that varies in this research is payload mass, m_l and also hoisting cable length, l. That means the PID controller is only optimum when the whole system is working using the parameters which was used during PID tuning. In other word, each time the parameter is changed in real life, PID controller has to be retuned, which makes it not practical in actual world.

This is where fuzzy logic plays a role. Fuzzy logic is used to evaluate error and error rate at each instance, and accordingly will tune the gains of PID to stabilize the output. In other word fuzzy-tuned PID is an adaptive PID controller because the gains of PID changes according to error. Fuzzy-tuned PID controller used in this paper is shown in Figure 3.2 below.

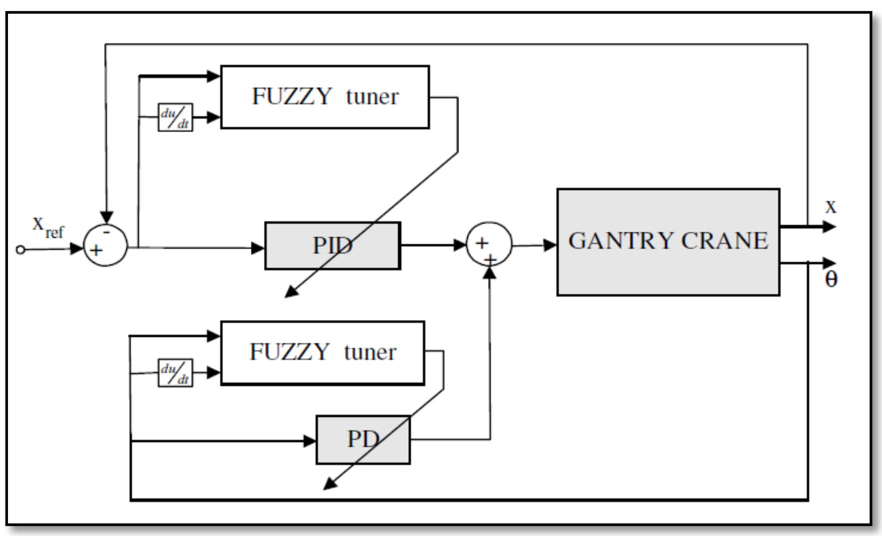


Figure 3.2 Fuzzy-tuned PID Controller Scheme

The tuned PID gains will be used as a base for Fuzzy tuning along with parameter variations. These PID gains will be obtained by first setting crane parameters to a nominal value of payload mass and cable length. Nominal values of cable length and payload mass used in the controlled design are $l = 0.5\ m$ and $m_l = 0.5\ kg$. The response of position and vibration control will be evaluated by comparing responses from PID and fuzzy-tuned PID controller.

On top of that, a very crucial assumption made for the initial part of the control design is that vibration control will be optimized if position control is optimized. Thus for PID control design, only position will be fed back into the controller. However, once a good fuzzy-tuned PID managed to be obtained, crane vibration will also be fed back into the system to obtain more satisfying result. Finally improvised fuzzy-tuned PID controller will be implemented to the actual, non-linearized system to show robustness to parameters.

CHAPTER 4

MODELING AND CONTROL OF A GANTRY CRANE

4.1 MATHEMATICAL MODEL DERIVATION

4.1.1 INTRODUCTION

Gantry crane model which will be used in this project is shown in Figure 4.1. From the figure, it is observed that the load hanged at the end of the bar, which is rigid. At a particular time, the cart will move to x_1, the force that has been applied on the cart is u, the mass of the cart is m_C, the mass of load is m_L, the length of the bar is l, and the angle between the bar and vertical axis is θ.

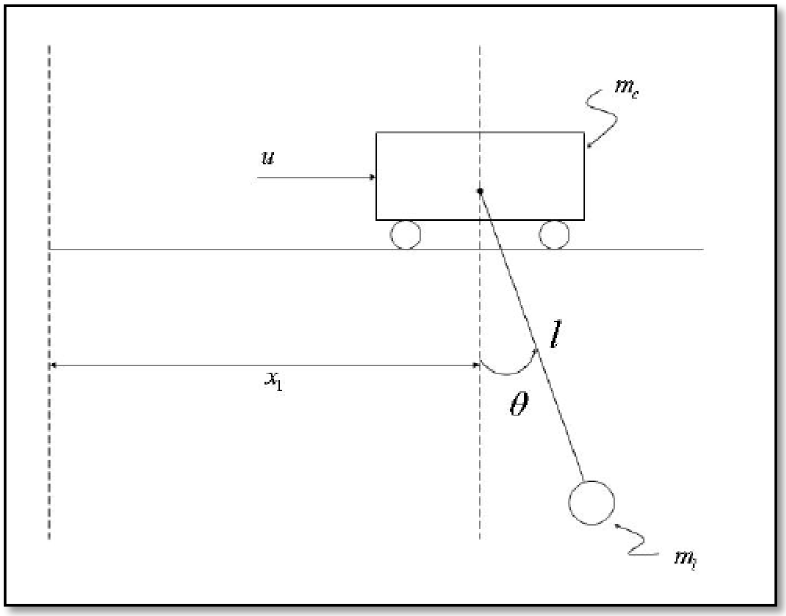


Figure 4.1 Gantry Crane Model

Assumptions made throughout the mathematical model derivation are as follows:

- The bar that connected between the cart and the hanged load is assumed to be rigid and massless.
- Friction force between the cart and the bridge is neglected.
- The angle and angular velocity of load swing, also rectilinear position and velocity of the cart are measurable.
- The load mass is concentrated at a point and the value of mass is exactly known.
- The cart's mass and the length of the connecting bar are exactly known.
- The hinged joint that connects the bar to the cart is frictionless.
- The trolley and the load move in the x-y plane.

4.1.2 MATHEMATICAL MODEL FOR A GANTRY CRANE

Mathematical model for this work was derived using Newton's Second Law [10]. The dynamics of the system was analyzed by splitting the system into two parts, which are cart and load.

For both cart and load, the free body diagram considered for mathematical derivation is shown in Figures 4.2 and 4.3 respectively.

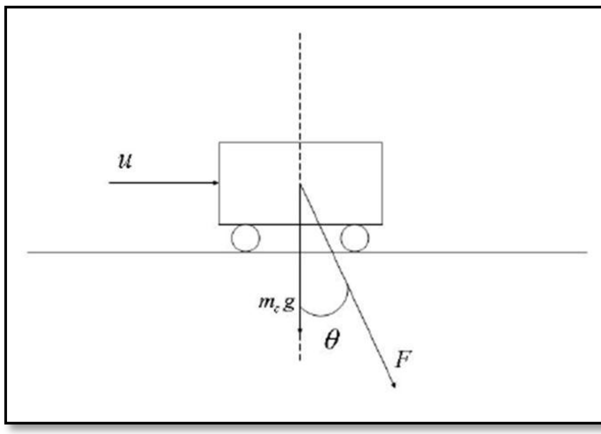


Figure 4.2 Cart's Free Body Diagram

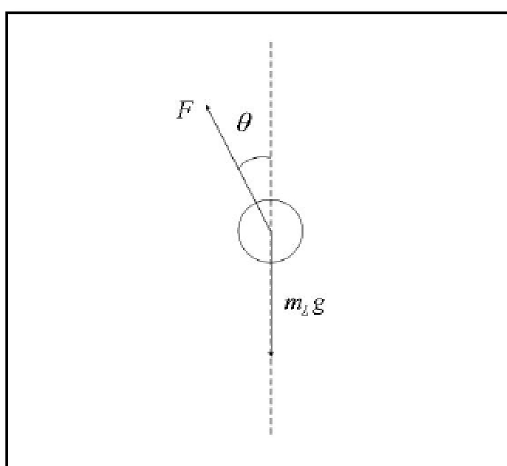


Figure 4.3 Load's Free Body Diagram

Note that F is assumed to be the longitudinal force caused by the bar. The bar is assumed to be thin and massless, which means that its gravitational effect, moment of inertia etc. that may give an effect to this rigid body can be neglected. Using kinetics characteristics, which relates the force and acceleration, the following equation can be derived:

i. Cart, horizontal:

$$\underset{+}{\rightarrow} \quad m_C \frac{d^2x_1}{dt^2} = u + Fsin\theta \tag{4.1}$$

ii. Cart, vertical:

$$\downarrow + \quad Fcos\theta + m_C g = 0 \tag{4.2}$$

iii. Load, horizontal:

$$\underset{+}{\rightarrow} \quad m_L \frac{d^2(x_1 + lsin\theta)}{dt^2} = -Fsin\theta \tag{4.3}$$

iv. Load, vertical:

$$\downarrow + \quad m_L \frac{d^2(lcos\theta)}{dt^2} = -Fcos\theta + m_L g \tag{4.4}$$

From equations (4.1) and (4.3),

$$m_c \frac{d^2x_1}{dt^2} = u - m_L \frac{d^2(x_1 + lsin\theta)}{dt^2}$$

$$m_c \frac{d^2x_1}{dt^2} + m_L \frac{d^2(x_1 + lsin\theta)}{dt^2} = u \tag{4.5}$$

From equations (4.3) and (4.4),

$$m_L \frac{d^2(lcos\theta)}{dt^2} = \frac{cos\theta}{sin\theta} \cdot m_L \frac{d^2(x_1 + lsin\theta)}{dt^2} + m_L g$$

$$m_L \frac{d^2(lcos\theta)}{dt^2} \cdot sin\theta - m_L \frac{d^2(x_1 + lsin\theta)}{dt^2} cos\theta = m_L g sin\theta \tag{4.6}$$

where

$$\frac{d^2(x_1+lsin\theta)}{dt^2} = \ddot{x}_1 + l\ddot{\theta}cos\theta - l\dot{\theta}^2 sin\theta \quad (4.7)$$

$$\frac{d^2(lcos\theta)}{dt^2} = -l\ddot{\theta}sin\theta - l\dot{\theta}^2 cos\theta \quad (4.8)$$

Summarizing equations (4.5), (4.6), (4.7), and (4.8) yields

$$(m_L+m_C)x_1 + m_L l\left(\ddot{\theta}cos\theta - \dot{\theta}^2 sin\theta\right) = u \quad (4.9)$$

$$m_L\ddot{x}_1 cos\theta + m_L l\ddot{\theta} = -m_L g sin\theta \quad (4.10)$$

$$x_1 cos\theta + l\ddot{\theta} = -g sin\theta \quad (4.11)$$

From equations (4.9) and (4.10), the equation can be rewritten in state space form as follows:

$$\begin{bmatrix} m_L + m_C & m_L l cos\theta \\ m_L cos\theta & m_L l \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} m_L l\dot{\theta}^2 sin\theta + u \\ -m_L g sin\theta \end{bmatrix}$$

Solving the above equation yields

$$\begin{bmatrix} x_1 \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{u+m_L sin\theta(l\dot{\theta}^2+gcos\theta)}{m_C+m_L sin^2\theta} \\ \frac{ucos\theta+m_L sin\theta\left(g+l\dot{\theta}^2 cos\theta\right)+gm_c sin\theta}{l(m_c+m_L sin^2\theta)} \end{bmatrix} \quad (4.12)$$

The obtained equation in (4.12) is a non-linear equation. It can’t be used for analysis, design or any other purpose because the calculation will be too complex. Thus it is easier to implement linearization to get a linear model. For that purpose, assumption considered was that deflection angle θ is small, and also has small angular velocity $\dot{\theta}$. That means we have to satisfy the following conditions:

$$\boxed{cos\theta \approx 1; sin\theta \approx \theta; sin^2\theta \approx 0; \dot{\theta}^2 \approx 0} \quad (4.13)$$

From equation (4.12) and considering the conditions of (4.13), the following equation was obtained

$$\begin{bmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{u+m_L g\theta}{m_C} \\ -\frac{u+m_L g\theta+g m_C\theta}{l m_C} \end{bmatrix}$$

$$= \begin{bmatrix} 0 & \frac{m_L}{m_C} g \\ 0 & -\frac{m_L+m_C}{l m_C} g \end{bmatrix} \begin{bmatrix} x_1 \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{1}{m_C} \\ -\frac{1}{l m_C} \end{bmatrix} u \qquad (4.14)$$

By assuming

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} x_1 \\ \dot{x}_1 \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} cart\ position \\ cart\ velocity \\ bar's\ angle \\ bar's\ angle\ rate \end{bmatrix}$$

the whole state equation can be written as follows:

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} \dot{x}_1 \\ \ddot{x}_1 \\ \dot{\theta} \\ \ddot{\theta} \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{m_L}{m_C} g & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{m_L + m_C}{l m_C} g & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m_C} \\ 0 \\ -\frac{1}{l m_C} \end{bmatrix} u$$

After obtain the state space equation, next step will be to configure this equation and simulate it using Matlab Simulink to analysis its step response.

4.2 MATLAB SIMULATION AND MODEL VERIFICATION

Matlab Simulink is used by putting the respective block functions according to our requirement and configures the values. For this study, the open-loop Simulink setup is shown as in Figure 4.4. Crane dynamics parameter setting for initial testing is shown in Figure 4.5.

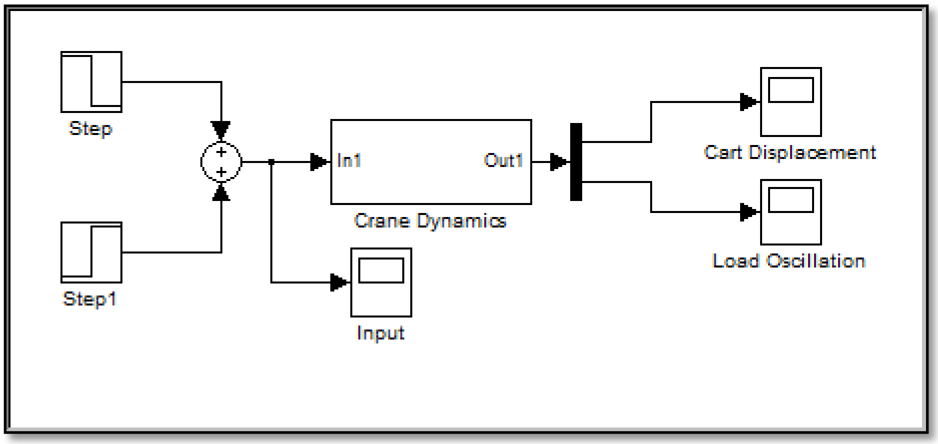


Figure 4.4 Simulink Setup for Gantry Crane

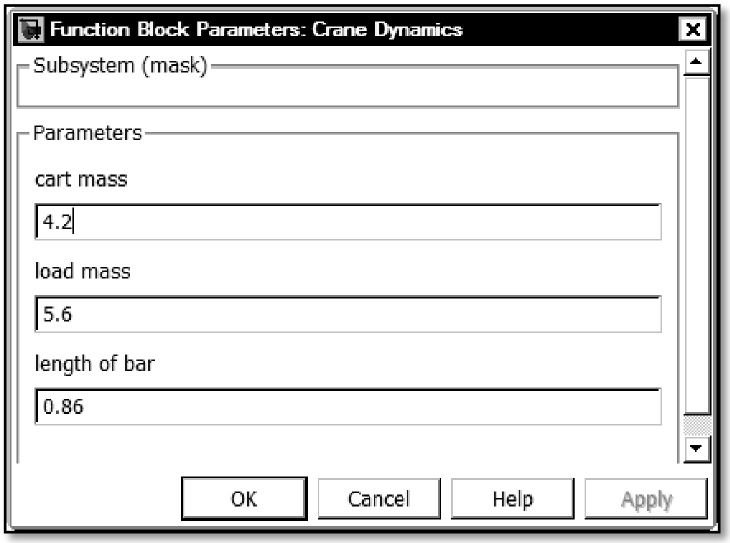


Figure 4.5 Settings of Gantry Crane Parameter Variable

As can be seen in Figure 4.4, two step input blocks are used as input source for the crane dynamics. For initial testing, gantry parameter variable were fixed at constant value as shown in Figure 4.5. For first simulation testing, input was given as 5 N for 0-1 second as shown in Figure 4.6.

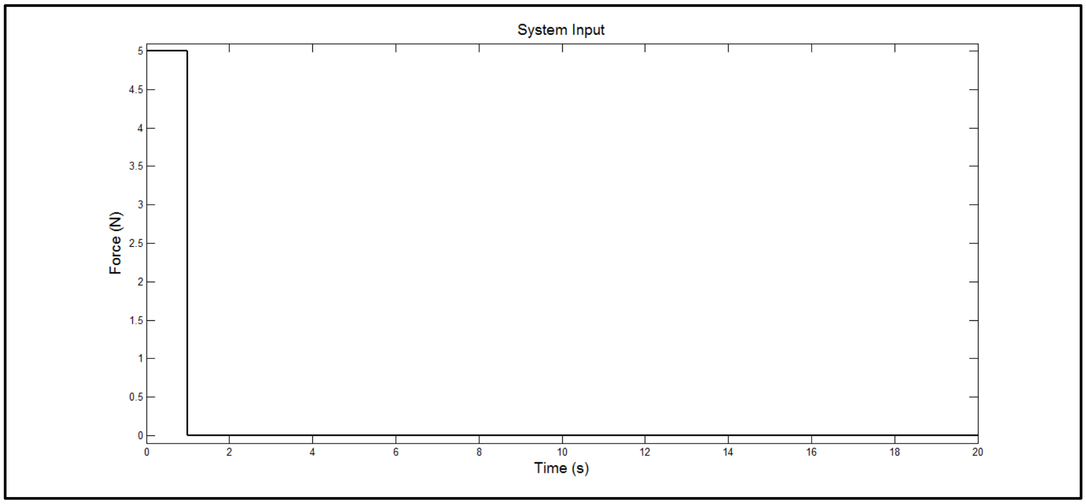


Figure 4.6 5N Pulse Input Setting

The resultant displacement and oscillation is as seen in Figure 4.7 and 4.8 respectively.

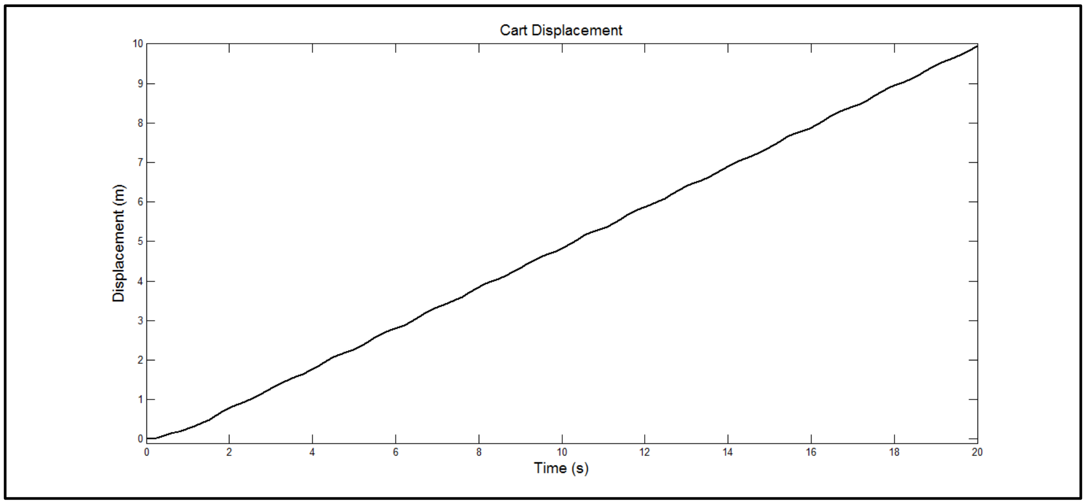


Figure 4.7 Cart Displacement for 5N Pulse Input

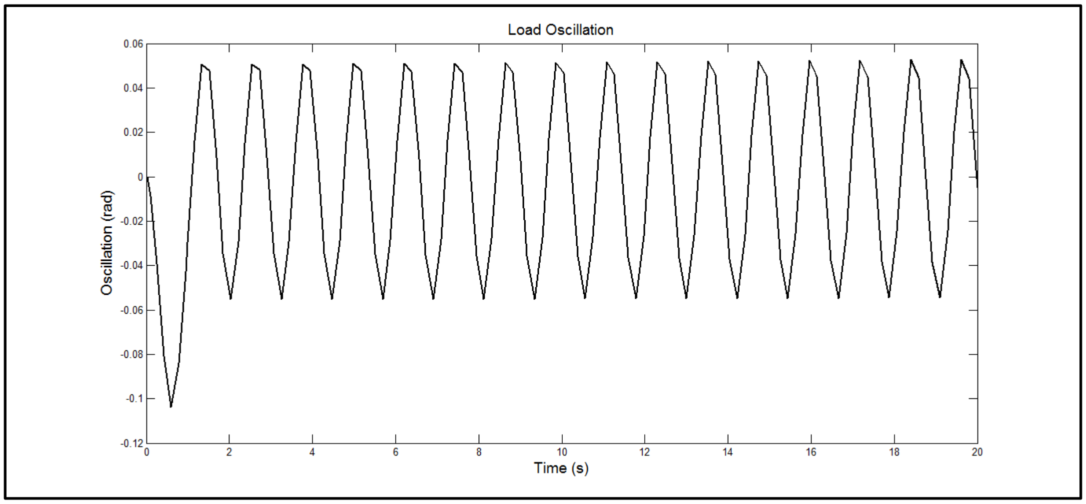


Figure 4.8 Load Oscillation for 5N Pulse Input

From Figures 4.7 and 4.8, the cart displacement moved to “infinity”, while the load swing is within -0.05 to 0.05 radians. From the observation, it is clear that the cart does not stop at all, and thus it is necessary for the input to be modified so that the cart will stop after a certain distance.

The solution for this problem was to use the “Bang Bang” rectangular function [11]. This type of input was considered because there is no other factor such as gravity which will make the cart stop since the model was formulated based on ideal conditions. Thus “Bang Bang” function is the solution in order to make the cart stop. According to Teo et al (1998), this type of input is known as a time-optimal solution. Figures 4.9, 4.10 and 4.11 shows the new input applied to the system, and the respective displacement and oscillation outputs.

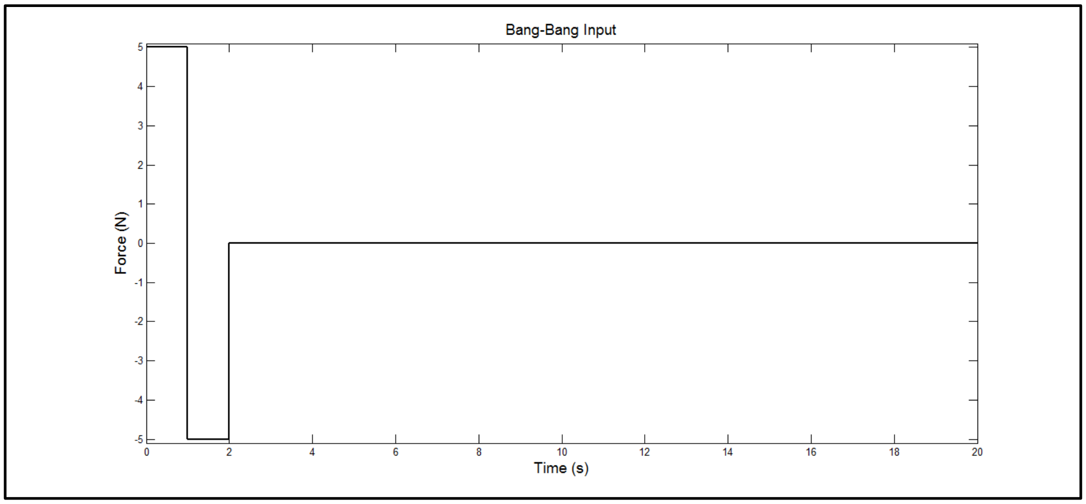


Figure 4.9 “Bang Bang” Input Setting

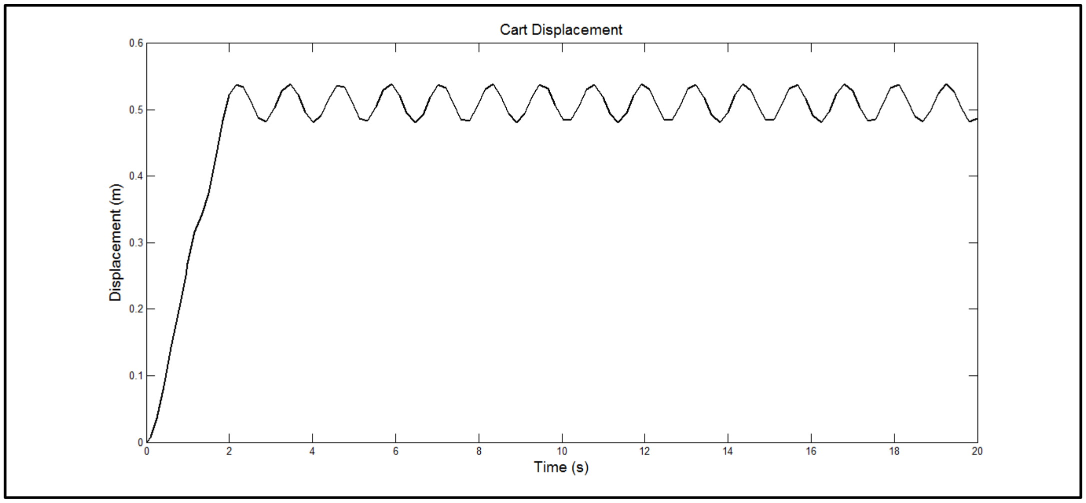


Figure 4.10 Cart Displacement for “Bang Bang” Input

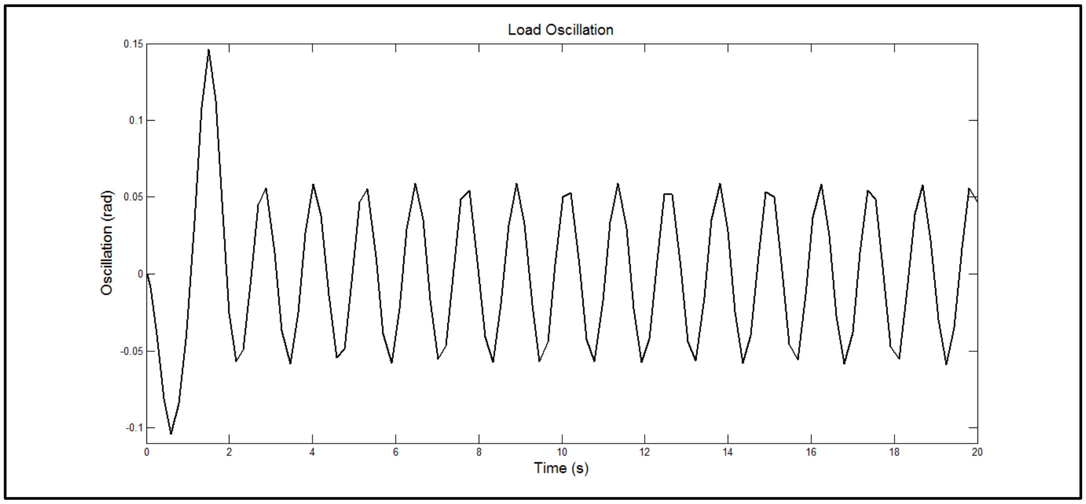


Figure 4.11 Load Oscillation for “Bang Bang” Input

Figures 4.10 and 4.11 basically represents the system response without any controller. After input was modified to be “Bang Bang” shape, the cart managed to stop after certain period, in this test it stopped between 1.84 and 1.9m. On the other hand, then load swing is around -0.057 to 0.055 radians. From the results, it can be concluded that with this configuration, an improvement on the system can be done through the right setting on the input.

When the value of payload is changed, the response of system in terms of cart position and load sway angle is also expected to change. Same goes for PID controller. An optimized PID controller for a fixed set of parameters would not yield an optimized response when the parameters are changed. This is because it is a nature of PID controller to not be able to satisfy the expected system performance when disturbance or parameter variance occurs. This can be rectified by implementing fuzzy-tuned PID controller.

The obtained result was verified by comparing with previous work which has similar crane system equation. For the purpose of this study, the results were compared with a previous thesis by Zairulazha Zainal [10]. Once the dynamic equation of gantry crane managed to be verified, next step is to design a PID controller, followed by fuzzy tuner for PID gains.

4.3 PID DESIGN FOR POSITION CONTROL

PID controller used for this project will be optimized using genetic algorithm. Cable length and payload mass used while tuning PID are nominal values, which are $0.5\ m$ and $0.5\ kg$ respectively. Since this project was focusing only fuzzy-tuned PID, tuning was done by implementing source code for genetic algorithm obtained from previous work [11]. Objective function used for genetic algorithm was based on minimization of Integral of Time Absolute Error (ITAE). The obtained PID values are as follows:

$$k_P = 26.64344, k_D = 26.42637, k_I = 0.0455$$

Using these values, the obtained step response of gantry crane are shown in Figures 5.3 and 5.4.

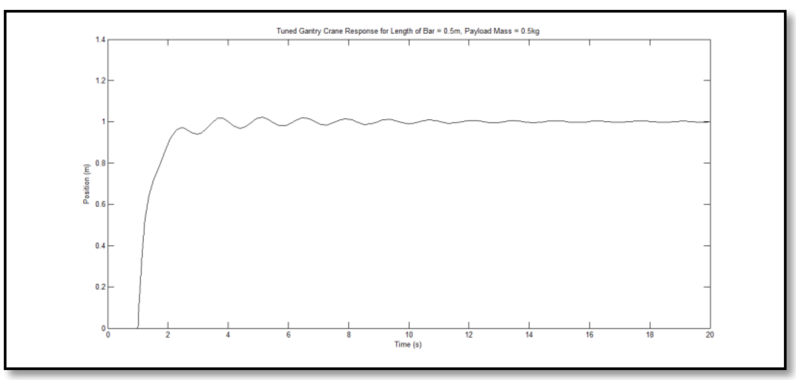


Figure 4.12 Gantry Crane Position Response for $l = 0.5\ m$ and $m_L = 0.5\ kg$

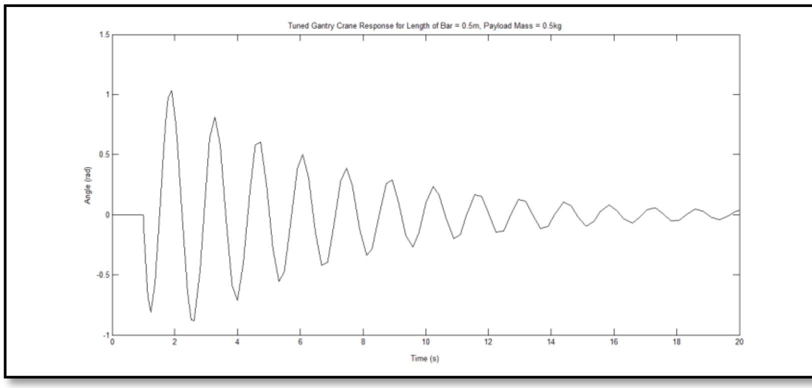


Figure 4.13 Gantry Crane Sway Response for $l = 0.5\ m$ and $m_L = 0.5\ kg$

From Figures 4.12 and 4.13 we can see that percentage of overshoot for crane position is 2.3% while settling time is 4.136 s. As for sway, maximum angle was 1.034 rad (59.24°) and settling time of 0.4 rad was 5.865 s.

4.4 FUZZY LOGIC AS PID GAINS TUNER FOR POSITION CONTROL

The fuzzy-tuned PID controller is then designed. The control structure is as shown in Figure 4.14.

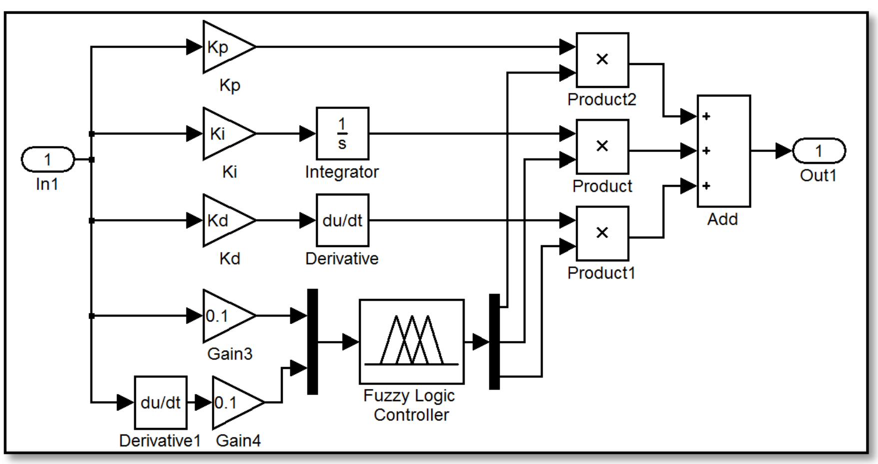


Figure 4.14 Fuzzy-tuned PID control scheme for gantry crane control

For the purpose of this project, mamdani fuzzy inference system has been designed as fuzzy-tuner. This system receives error and error rate as its input and has three different outputs, which are PID gains tuner.

The fuzzy system for the input has three triangular members. On other hand, output for k_P has three triangular members, while output for k_D and k_I consists of two triangular functions. The width of each membership was chosen according to determined range or universe of discourse. These values were constantly modified throughout the project to obtain the best result.

The range of fuzzy input for error was set up to from -1.087 to 1 and -1 to 0.1807 for error rate. Range of output was set up to 0 to 5 for k_P, 0 to 0.6 for k_I and 0 to 2.5 for k_D. The fuzzy membership for error and error rate is shown in Figures 4.15, 4.16 and 4.17.

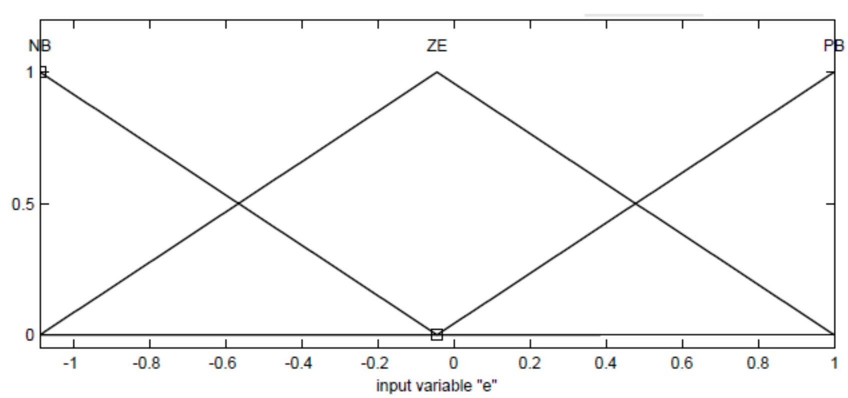


Figure 4.15 Fuzzy Membership for Fuzzy Input (Error)

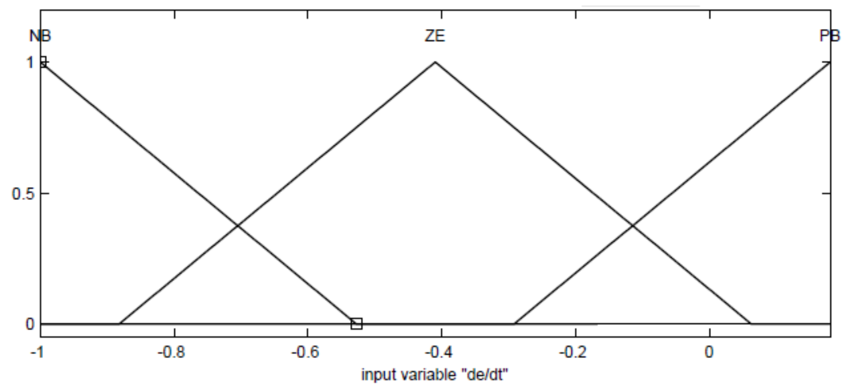
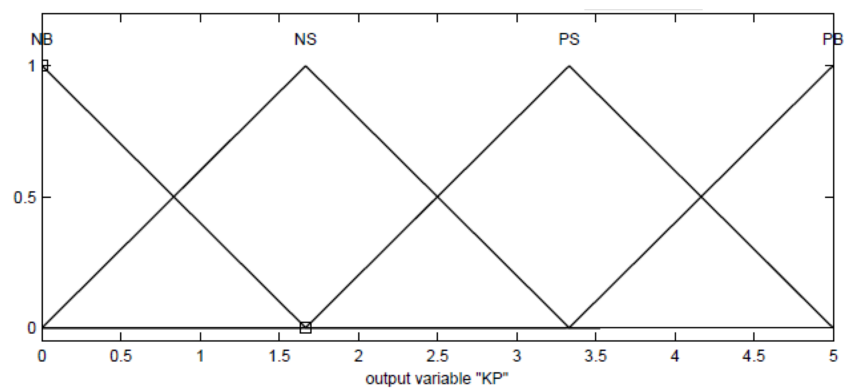
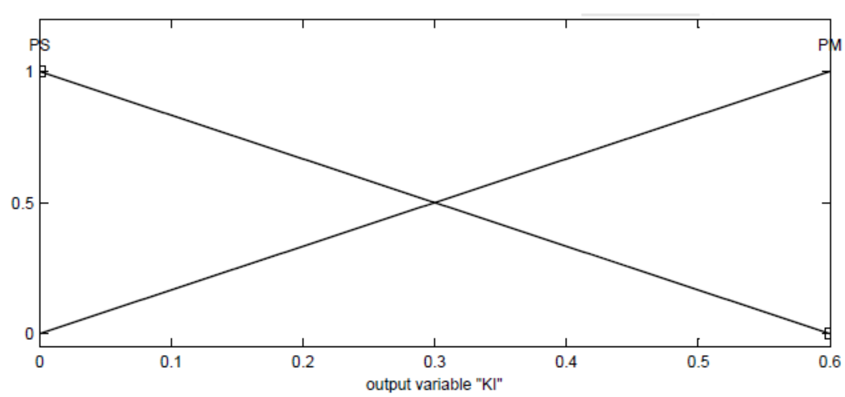


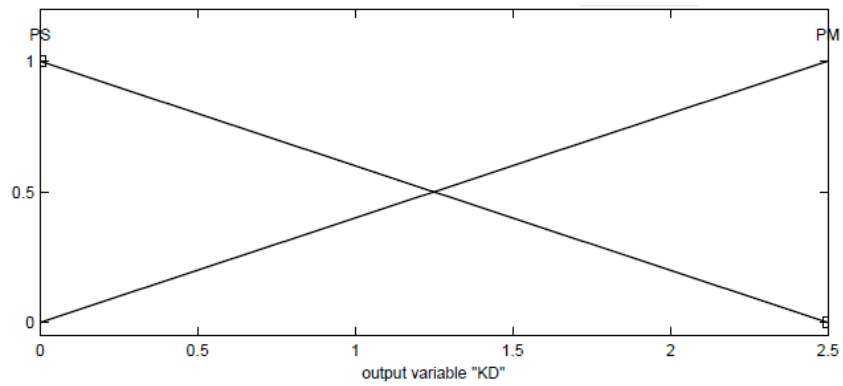
Figure 4.16 Fuzzy Membership for Fuzzy Input (Error Rate)



(a) Fuzzy Membership for k_P



(b) Fuzzy Membership for k_I



(c) Fuzzy Membership for k_D

Figure 4.17 Fuzzy Memberships for Fuzzy Output

The fuzzy rules were done based on Macvicar-Wheelan Matrix [9]. The rules table for fuzzy tuner is shown in Tables 4.1, 4.2, and 4.3 while table 4.4 shows the meaning of abbreviations used in Tables 4.1, 4.2, and 4.3.

Table 4.1 Fuzzy Rule Base for k_P

k_P	Error Rate			
Error		**NB**	**ZE**	**PB**
	NB	-	NB	-
	ZE	NS	-	PS
	PB	-	PB	-

Table 4.2 Fuzzy Rule Base for k_I

k_I	Error Rate			
Error		**NB**	**ZE**	**PB**
	NB	-	PS	-
	ZE	PS	-	PM
	PB	-	PS	-

Table 4.3 Fuzzy Rule Base for k_D

k_D	Error Rate			
Error		**NB**	**ZE**	**PB**
	NB	-	PS	-

	ZE	PM	-	PM
	PB	-	PS	-

Table 4.4 Rule Base Abbreviations

NB	Negative Big
ZE	Zero
PB	Positive Big
PS	Positive Small
PM	Positive Medium
NS	Negative Small

From the tables above, it can be observed that only four conditions were considered for each output rule making. More conditions can be considered for future improvement of this project. Before go to further explanation of rulemaking conditions, overview of rule is shown in Figure 4.18.

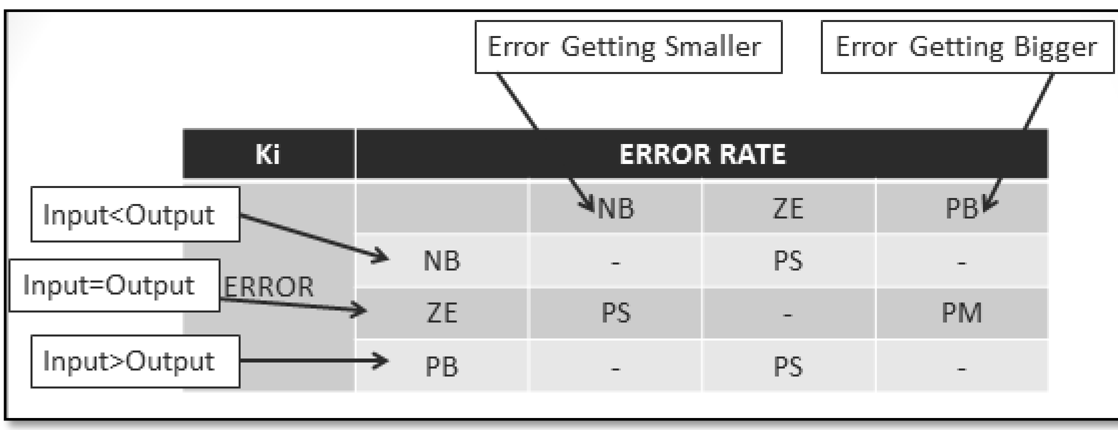


Figure 4.18 Overview of Rule Base

For condition 1 which is NB and ZE (Input < Output and error rate zero), it means clear meaning that output is bigger than input, and that it is currently not moving (error rate zero). Thus appropriate action is reducing input signal by reducing PID values as follows:

k_P=NB, k_I=PS, k_D=PS

Condition 2 is ZE and NB (Input = Output and error rate is getting smaller). It means the steady state is reached and error rate is getting smaller. At this condition, it is suitable to increase k_D gain to decrease overshoot and also settling time, resulting in change of PID gains as follows:

k_P=NS, k_I=PS, k_D=PM

Condition 3 is ZE and PB (Input = Output and error rate getting bigger). This means that steady state is reached but error rate is getting bigger, which means overshoot will happen. Thus we increase k_D to decrease overshoot and settling time. We also increase k_I to eliminate steady state error. PID gains will change as follows:

k_P=NB, k_I=PS, k_D=PS

Last condition is PB and ZE (Input > Output and error getting bigger). That means output is less than input. So we increase k_P to increase overshoot so that input can be reached. PID gain changes are as follows:

k_P=PB, k_I=PS, k_D=PS

The overall performance of the controller is determined by the range of each fuzzy output because it will function as weight for PID value tuning. As mentioned before, the optimization to obtain PID for position and vibration control for gantry crane was obtained using genetic algorithm. These values are used as a baseline for weighting factors in the fuzzy-tuned PID controller to allow robustness in the PID controller. For simplicity, the same characteristic of fuzzy-tuned PID in terms of fuzzy rules and fuzzy membership is used for fuzzy-tuned PD later on.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 SIMULATION RESULTS

Simulations were done using Matlab Simulink. The first part of the research was done using a linearized model of gantry crane, while once the full construction of control design is complete, non-linearized model was used. The setup for both linearized and non-linearized model is shown in Figures 5.1 and 5.2. Linearized model was implemented by using built-in “state-space” block because the model was in typical state space form. Non-linearized on other hand was implemented using built-in “function” block because of non-linear form of equation such as trigonometry functions.

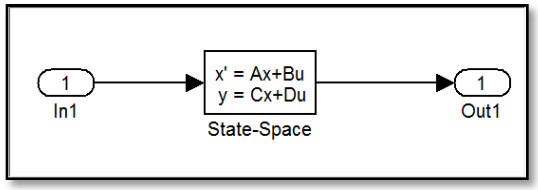


Figure 5.1 Function Block Setup for Linearized Crane Model

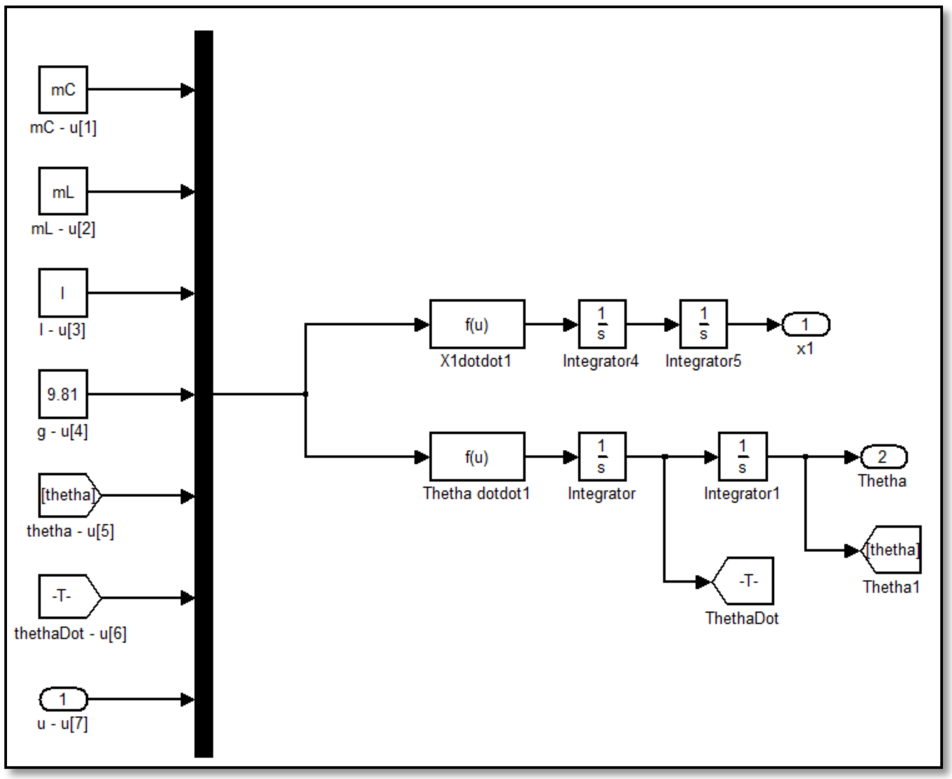


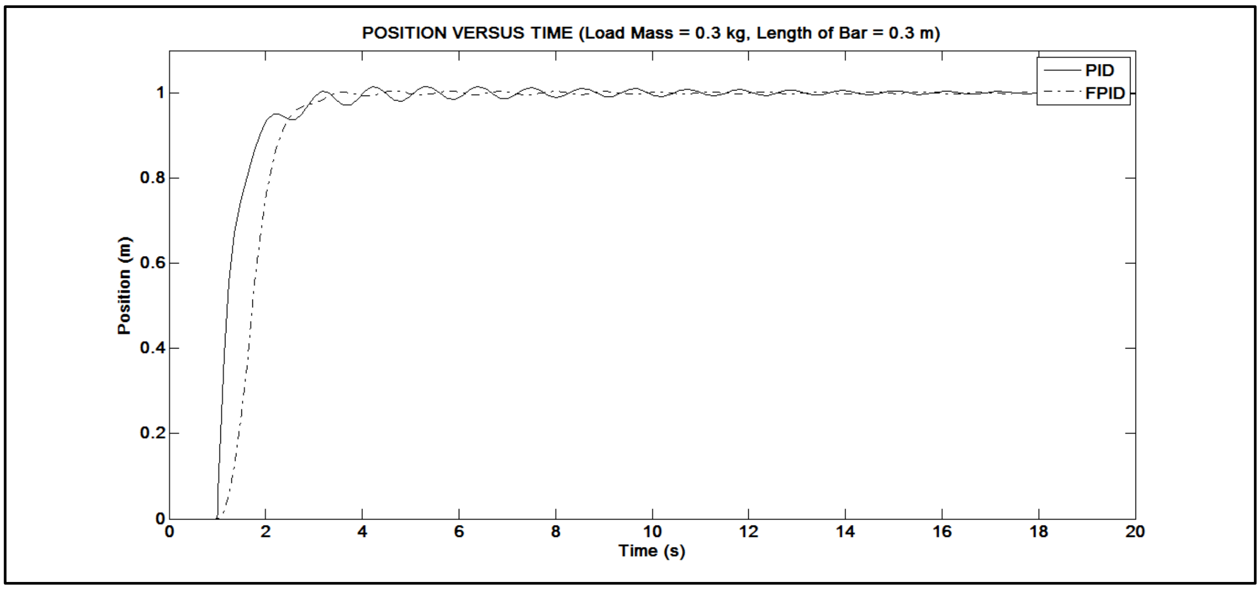
Figure 5.2 Function Block Setup for Non-Linearized Crane Model

5.1.1 LINEARIZED SYSTEM (PID AND FUZZY-TUNED PID)

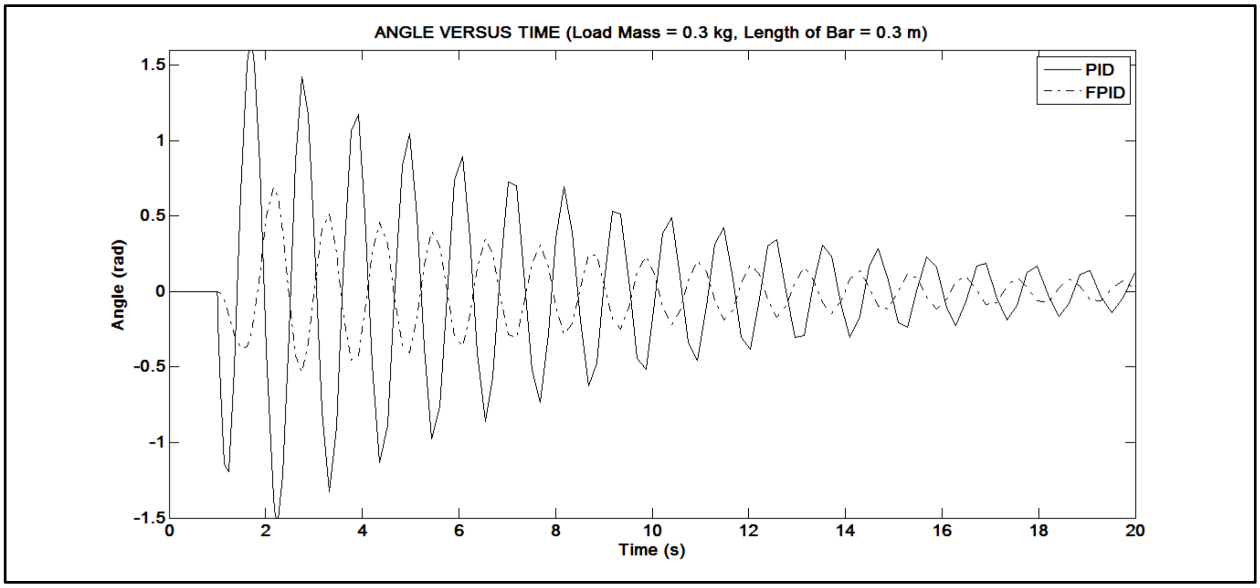
PID controller was tuned beforehand using genetic algorithm for nominal values of length of bar of 0.5m and payload mass of 0.5kg and the obtained PID parameters were

$$k_P = 26.64344, k_D = 26.42637, k_I = 0.0455$$

Next step was to obtain position and sway response of gantry crane for various parameter changes. For the various parameter changes, PID was tuned adaptively by using fuzzy logic. Figures 5.3 and 5.4 shows position and sway response of a gantry crane for 2 different parameters. Table 5.1 and 5.2 summarizes comparison of gantry crane response from PID and Fuzzy-tuned PID (FPID) controller for all set of parameter changes considered in this project. Settling time for sway angle was taken when angle becomes less than 0.4 rad (22.9°).

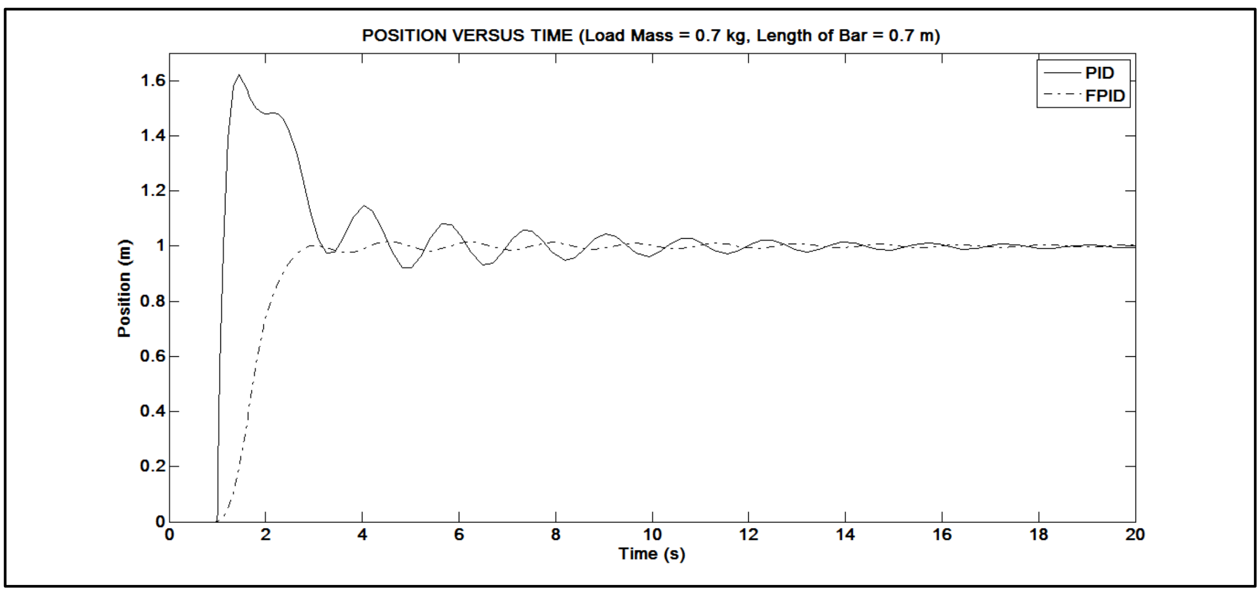


(a) Gantry Crane Position Response

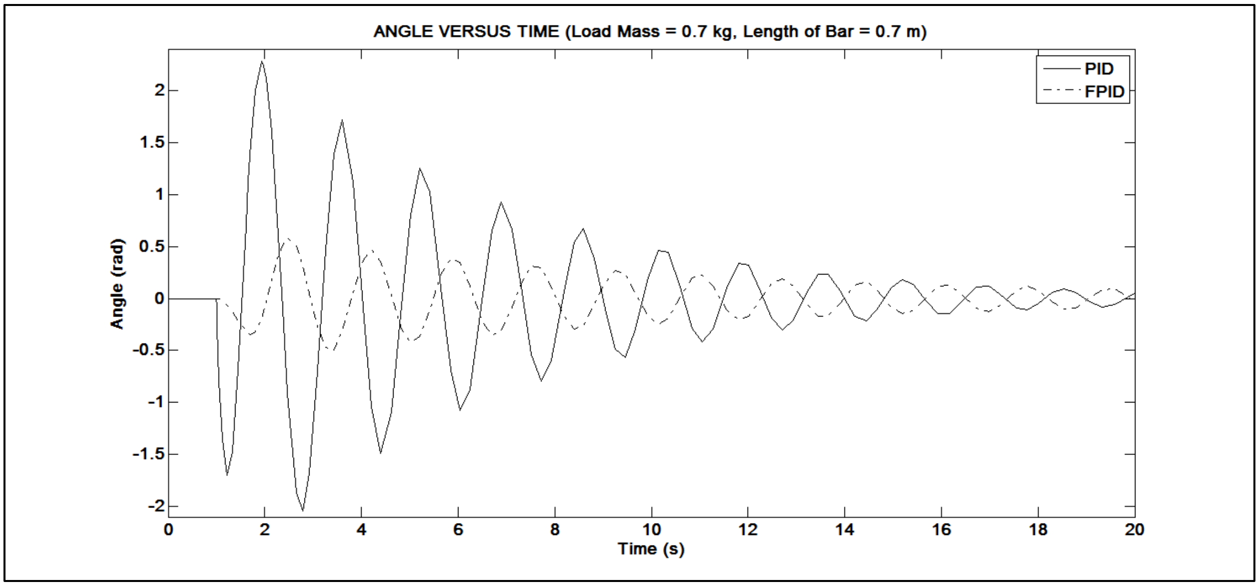


(b) Gantry Crane Sway Response

Figure 5.3 Gantry Crane Response for PID and FPID ($l = 0.3\ m$ and $m_L = 0.3\ kg$)



(a) Gantry Crane Position Response



(b) Gantry Crane Sway Response

Figure 5.4 Gantry Crane Response for PID and FPID ($l = 0.7\ m$ and $m_L = 0.7\ kg$)

Table 5.1 Positioning Response Comparison of PID and FPID

l, m	m_L, kg	PID		FPID	
		$OS, \%$	T_s, s	$OS, \%$	T_s, s
0.3	0.3	1.6	2.8415	0.5	2.088
	0.5	1.9	3.538	0.8	1.882
	0.7	1.8	3.946	0.9	1.76
0.5	0.3	63.1	8.53	0.7	2.089
	0.5	2.3	4.136	1.2	2.275
	0.7	2.6	6.409	1.5	1.72
0.7	0.3	0.6	3.027	0.7	2.144
	0.5	59.8	9.01	1.5	2.472
	0.7	62.1	12.2	1.8	2.82

Table 5.2 Anti-Swing Response Comparison of PID and FPID

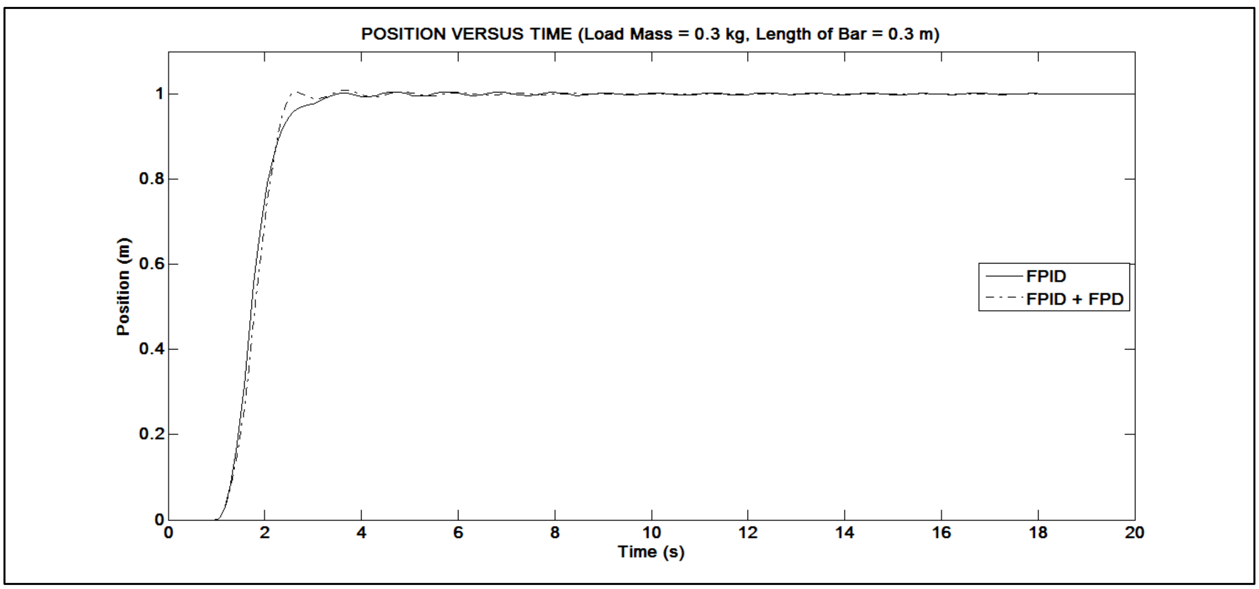
l, m	m_L, kg	PID		FPID	
		$Max.rad$	T_s, s	$Max.rad$	T_s, s
0.3	0.3	1.69	10.48	0.6858	5.443
	0.5	1.1135	10.04	0.682	7.727
	0.7	0.8246	8.532	0.6195	9.99
0.5	0.3	4.664	10.76	0.6135	2.39
	0.5	1.034	5.865	0.6423	4.906
	0.7	0.8521	5.936	0.6062	5.739
0.7	0.3	0.6399	1.815	0.5633	1.374
	0.5	3.022	8.577	0.6316	3.484
	0.7	2.277	10.06	0.5819	4.018

From Figure 5.3 and 5.4, it can be observed, that FPID has overall better performance compared PID. Figure 5.4 (a) shows that PID controller does not have a good robust property because it produces large overshoot for small variance of load mass and bar length.

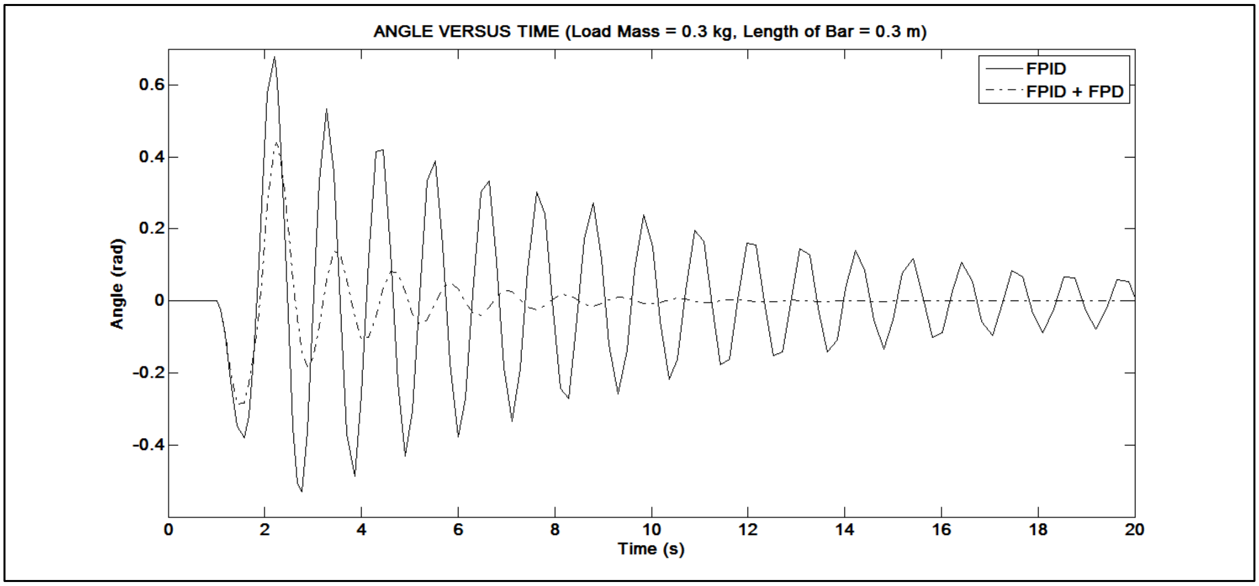
Table 5.1 shows FPID results in overall better response in terms of percentage of overshoot and also settling time. It is also observable that the highest percentage of overshoot for FPID is 1.8% which makes it more suitable than PID controller for usage in environment with constant parameter change. Table 5.2 also shows that FPID yields a much better performance of sway angle.

5.1.2 LINEARIZED SYSTEM (FUZZY-TUNED PID AND FUZZY-TUNED PID + FUZZY-TUNED PD)

Next is the comparison of FPID with FPID plus fuzzy-tuned PD (FPD). The latter has two feedbacks, which are each for position and anti-sway respectively. The purpose of FPID plus FPD is to obtain a better controller which has smoother response for anti-sway. Figures 5.5 and 5.6 shows position and sway response of a gantry crane for 2 different parameters. Tables 5.5 and 5.6 summarizes the comparison between both the controllers. Settling time for sway angle was taken when angle becomes less than 0.2 rad (11.45°).

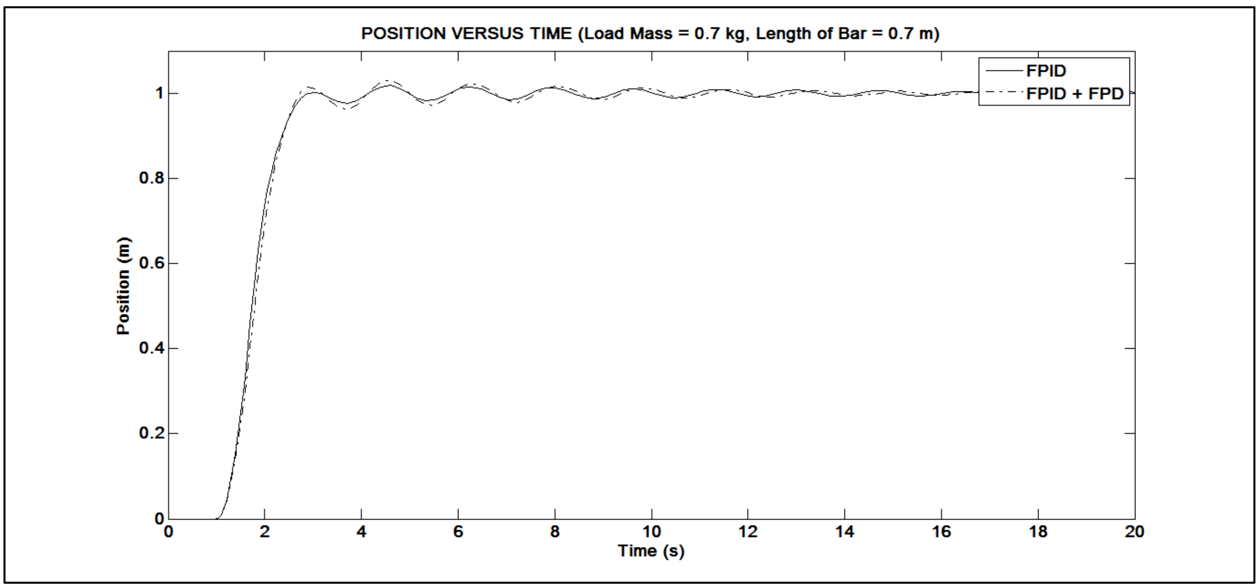


(a) Gantry Crane Position Response

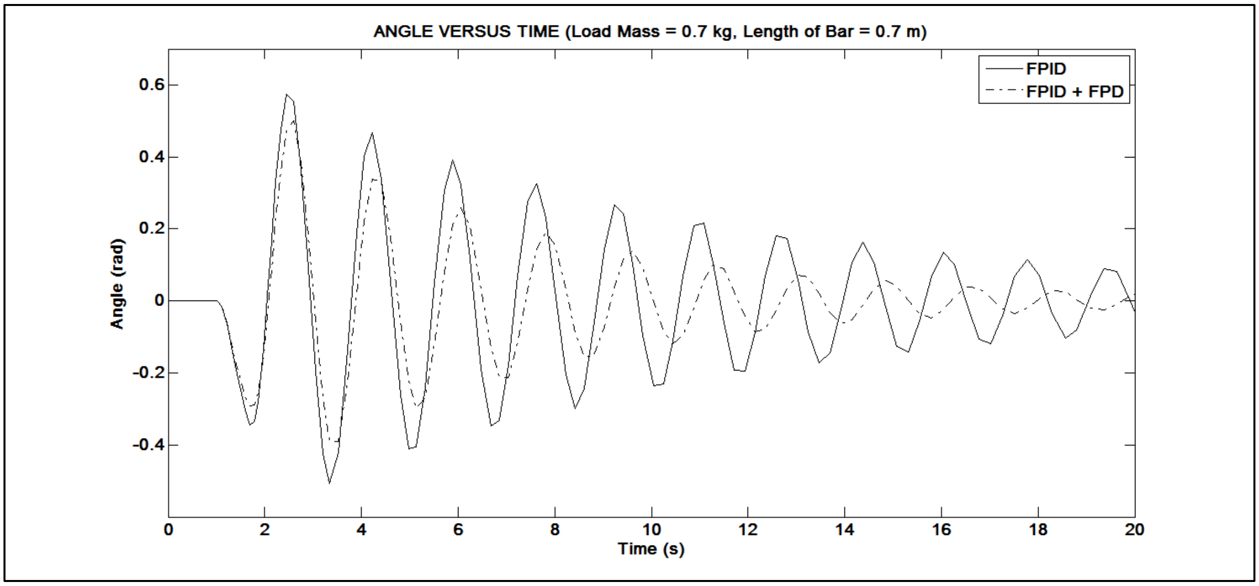


(b) Gantry Crane Sway Response

Figure 5.5 Gantry Crane Response for FPID and FPID+FPD ($l = 0.3\ m$ and $m_L = 0.3\ kg$)



(a) Gantry Crane Position Response



(b) Gantry Crane Sway Response

Figure 5.6 Gantry Crane Response for FPID and FPID+FPD ($l = 0.7\ m$ and $m_L = 0.7\ kg$)

Table 5.3 Positioning Response Comparison of FPID and FPID plus FPD

l, m	m_L, kg	FPID		FPID + FPD	
		OS, %	T_s, s	OS, %	T_s, s
0.3	0.3	0.5	2.088	0.9	1.399
	0.5	0.8	1.882	2.3	4.529
	0.7	0.9	1.76	2.7	7.035
0.5	0.3	0.7	2.089	1.7	1.501
	0.5	1.2	2.275	2.3	3.869
	0.7	1.5	1.72	2.9	6.288
0.7	0.3	0.7	2.144	2.8	1.823
	0.5	1.5	2.472	2.2	3.306
	0.7	1.8	2.82	3.2	6.234

Table 5.4 Anti-Swing Response Comparison of FPID and FPID plus FPD

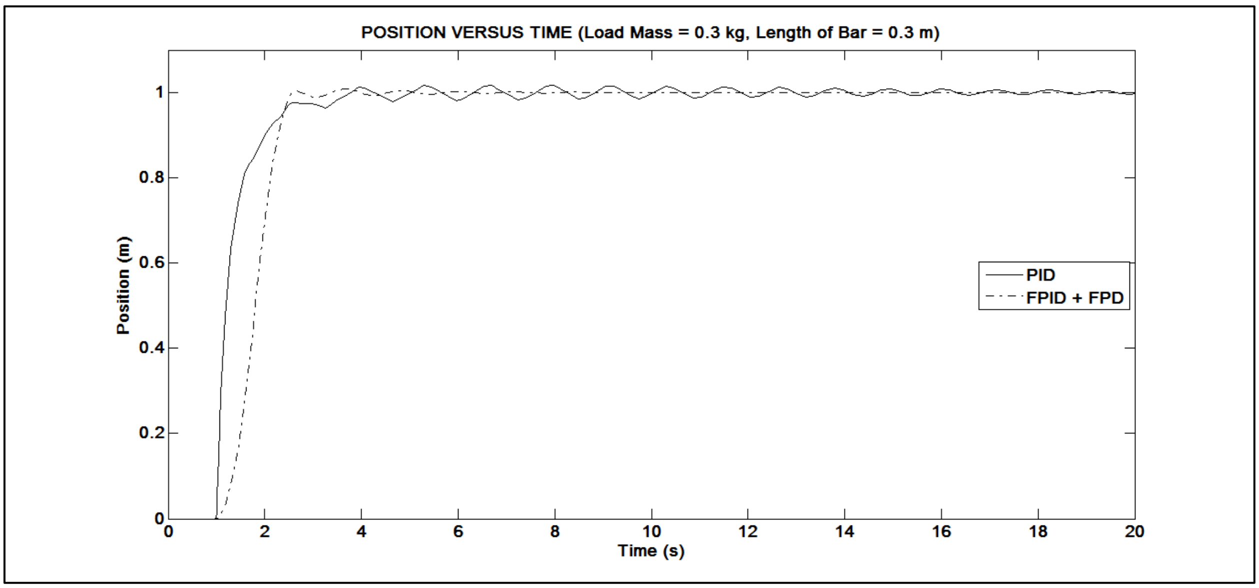
l, m	m_L, kg	PID		FPID	
		$Max.rad$	T_s, s	$Max.rad$	T_s, s
0.3	0.3	0.679	9.37	0.4388	1.499
	0.5	0.674	18.44	0.54	5.992
	0.7	0.6236	>20	0.5435	9.39
0.5	0.3	0.6156	6.117	0.3965	1.546
	0.5	0.6588	10.61	0.5126	4.58
	0.7	0.6023	14.23	0.524	6.868
0.7	0.3	0.5612	3.902	0.3658	1.464
	0.5	0.614	7.839	0.4871	3.639
	0.7	0.5749	10.08	0.5001	6.032

Figures 5.5 (a) and 5.6 (a) reveals that FPID + FPD has slightly deteriorated in terms of positioning response compared to FPID controller. This can be seen from the longer settling time for FPID + FPD. However this was justified because it managed to perform much better in terms of oscillation. This is showed in Figures 5.5 (b) and 5.6 (b). FPID + FPD has a faster settling time and also lower maximum angle compared to FPID.

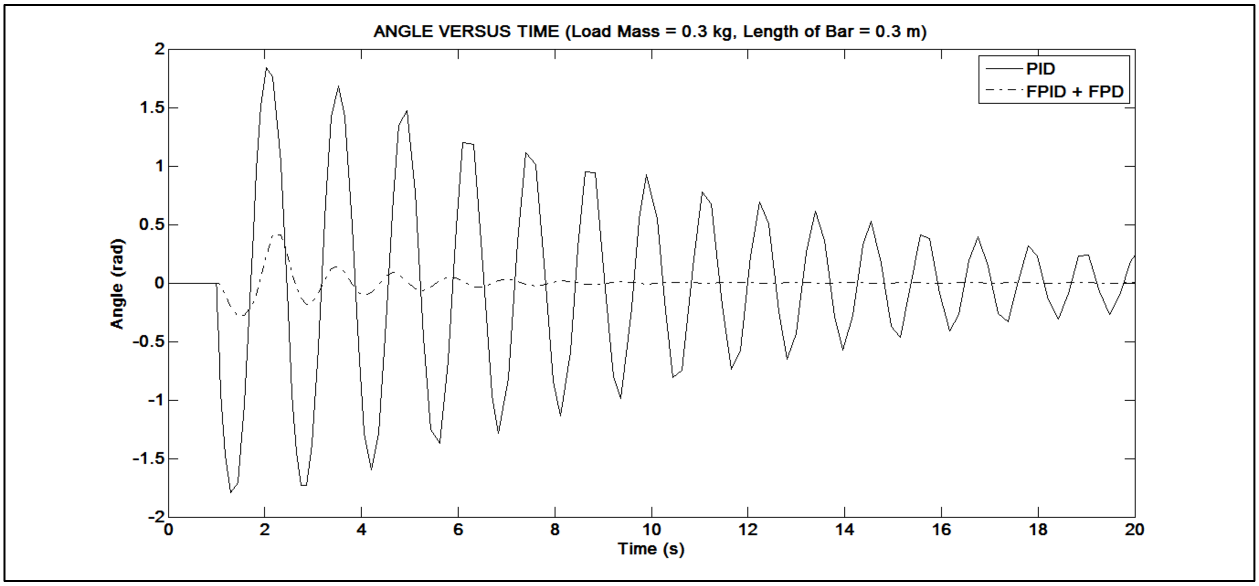
Tables 5.3 and 5.4 show performance of gantry crane for the whole set of parameter variations. Overall, even though position response of FPID + FPD is not as good as FPID, it managed to compensate it by producing a smoother response for anti-sway control. In other words, FPID + FPD has an overall better performance compared to FPID alone in maintaining both position and anti-sway.

5.1.3 ACTUAL SYSTEM (PID AND FUZZY-TUNED PID + FUZZY-TUNED PD)

Lastly the PID of initial design and FPID+FPD controller is compared again, this time by testing it on actual crane model system, which is non-linearized. Figures 5.3 and 5.4 shows position and sway response of a gantry crane for 2 different parameters. The overall performance of gantry crane measured is summarized in Table 5.5 and 5.6 below. Settling time for sway angle was taken when angle becomes less than 0.2 rad (11.45°).

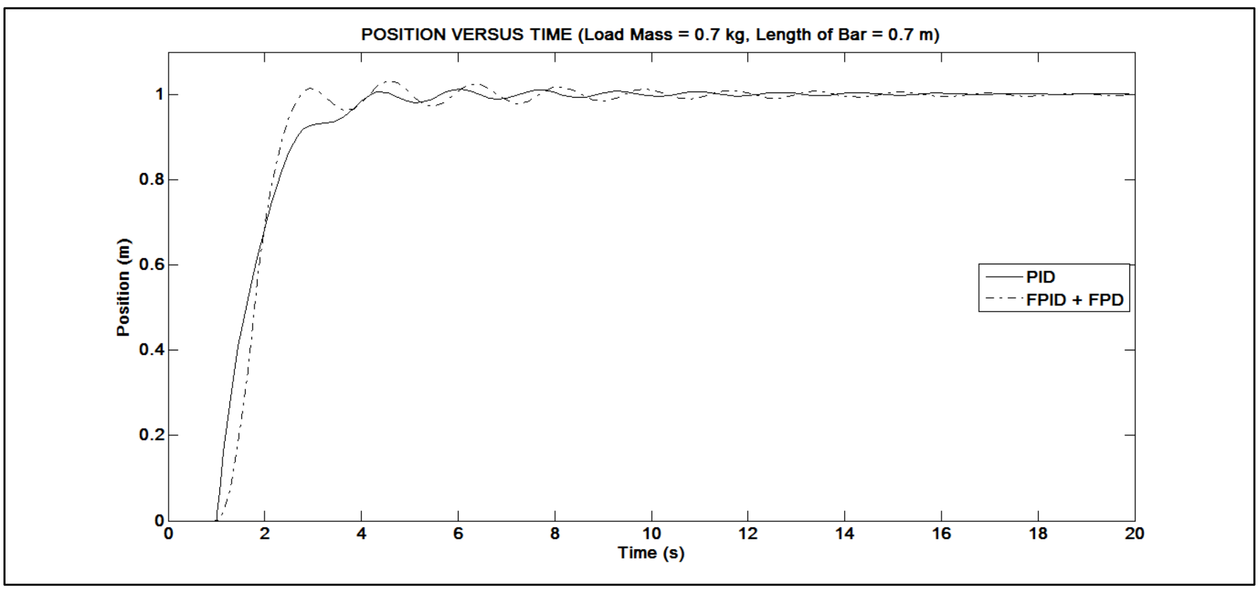


(a) Gantry Crane Position Response

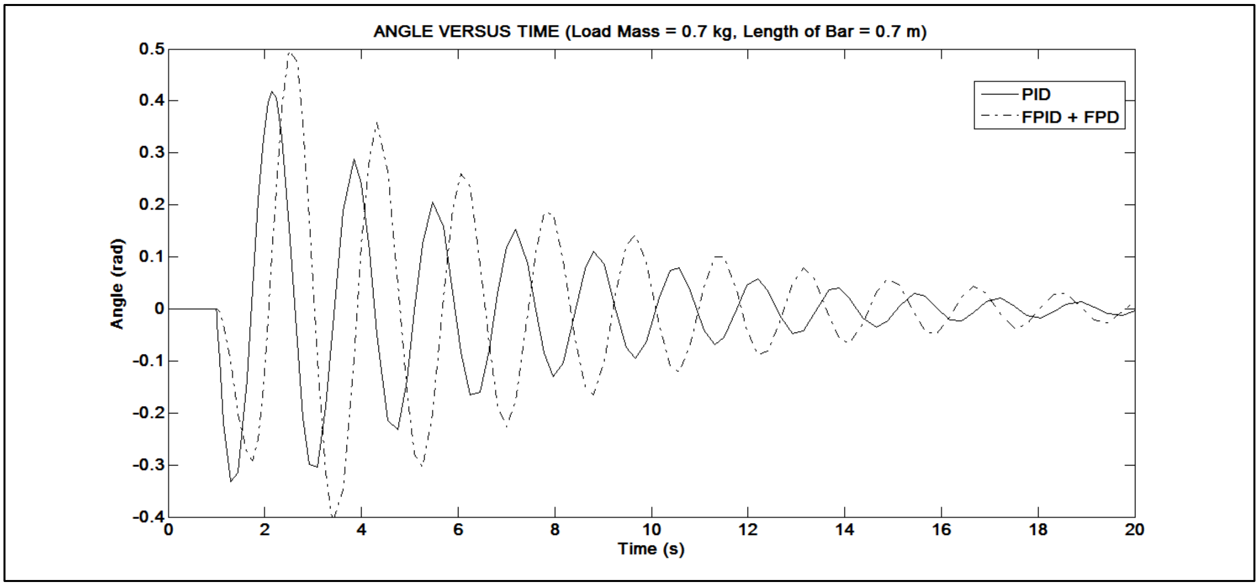


(b) Gantry Crane Sway Response

Figure 5.7 Gantry Crane Response for PID and FPID+FPD on Actual System ($l = 0.3\ m$ and $m_L = 0.3\ kg$)



(a) Gantry Crane Position Response



(b) Gantry Crane Sway Response

Figure 5.8 Gantry Crane Response for PID and FPID+FPD on Actual System ($l = 0.7\ m$ and $m_L = 0.7\ kg$)

Table 5.5 Positioning Response Comparison of PID and FPID + FPD on Actual System

l, m	m_L, kg	PID		FPID + FPD	
		$OS, \%$	T_s, s	$OS, \%$	T_s, s
0.3	0.3	1.8	3.654	0.9	1.479
	0.5	1.9	3.904	2.2	4.626
	0.7	1.7	4.19	2.6	7.056
0.5	0.3	3	6,839	1.7	1.482
	0.5	2.7	6.069	2.4	3.875
	0.7	74.5	INF	2.9	6.264
0.7	0.3	83.7	INF	3.5	1.959
	0.5	0.9	3.936	2.3	3.252
	0.7	1.3	3.001	3.2	5.463

Table 5.6 Anti-Swing Response Comparison of PID and FPID + FPD on Actual System

l, m	m_L, kg	PID		FPID	
		$Max.rad$	T_s, s	$Max.rad$	T_s, s
0.3	0.3	1.843	>20	0.4133	1.479
	0.5	1.159	>20	0.5473	6.056
	0.7	0.8297	>20	0.5364	9.47
0.5	0.3	1.853	12.64	0.399	1.482
	0.5	1.132	11.2	0.5057	4.543
	0.7	33.7	INF	0.5235	7.679
0.7	0.3	71.63	INF	0.375	1.576
	0.5	0.4478	4.142	0.49	3.766
	0.7	0.4182	4.465	0.4969	6.185

Figures 5.7 and 5.8 shows the response of gantry crane on actual, non-linearized system for $l = 0.3\,m$ and $m_L = 0.3\,kg$ and for $l = 0.7\,m$ and $m_L = 0.7\,kg$. From Figures 5.7 (a) and 5.8 (a), it is observable that both the controllers yield a considerable satisfying response. However, in terms of sway angle, response of PID controller as shown in 5.7 (b) is too high in magnitude for maximum sway angle. Meanwhile in 5.8 (b), settling time of PID is much faster.

However, from Table 5.6, it is observable that for parameters of for $l = 0.5\,m$ and $m_L = 0.7\,kg$ and $l = 0.7\,m$ and $m_L = 0.3\,kg$, PID output sway angle becomes infinity. This shows that PID controller could not cope with parameter changes and results in unstable system. FPID + FPD do not have this problem because it was able to cope with parameter changes to yield satisfying results.

5.2 DISCUSSIONS

If PID and FPID compared, FPID has a better ability of robustness which enables it to cope with parameter change. FPID can be further improved by adding another feedback for anti-sway control. This improved controller, in form of FPID + FPD might not be the best position controller or anti-sway controller, but it does have a good balance between both of them and results in overall better performance.

CHAPTER 6

CONCLUSION AND FUTURE RECOMMENDATION

6.1 CONCLUSION

From the results in chapter 5, it is proven that the proposed FPID controller has overall advantage of robustness compared to PID controller. It has an even better overall performance in terms of both position and anti-sway by implementing FPID + FPD. Simple design of PID, added with fuzzy logic makes it a practical control for use in real life. On top of that we do not have to re-tune the controller each time parameters of the crane change, because everything is done by fuzzy logic.

6.2 FUTURE RECOMMENDATION

Performance of the current FPID + FPD can be improved in future by making some amendments to current procedure. The first is genetic algorithm which used to optimize PID gains can be modified to take into consideration of both the position and sway angle of payload. In this project, only single output was considered during genetic algorithm implementation.

Next, fuzzy rule base used in this project was obtained by considering only four conditions of input because of time constraint. It can be further improved by taking into consideration all nine conditions of fuzzy input. By doing that, it is possible to achieve a more sophisticated PID tuner which is robust to wider range of crane parameter variations.

The width of fuzzy memberships for both input and output also can be modified by conducting experiment in order to achieve a more human like PID tuning ability. Fuzzy membership also can be added in order to enhance the ability of the fuzzy PID tuner.

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