HYBRID PID WITH INVERSE MODEL CONTROL OF POSITION AND SWAY ANGLE FOR A 2D GANTRY CRANE SYSTEM

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FEBRUARY, 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.

……………………………………..

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CERTIFICATION

This is to certify that the research work for this thesis and the subsequent write-up by Osaweremen Jude Aienoleyboise - SPS/15/MEE/00018 were carried out under my supervision.

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APPROVAL

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

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

DEDICATION

This research work is dedicated to my mother Mrs. Akele Rachael. May God Almighty continue to keep you alive to eat the fruit of your labour amen.

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LIST OF SYMBOLS AND ABBREVIATIONS

θ : Sway Angle.

P: Proportional controller

PI: Proportional integral controller

PID: Proportional integral derivative controller

T: Time taken

K_p : Proportional gain

K_i : Integral gain

K_d : Derivative gain

u(t) : Control Signal.

e(t): Undesired Error

(*Ti*) : Integral time

Td : Derivative time

IMC: Inverse Model Controller

m_1: mass of the trolley

m_2: mass of the payload

l: Length of rope

g: Gravity acceleration

θ: Angle of load swing

x: Position of trolley

$\ddot{x}$: Acceleration of trolley

$\ddot{\theta}$: Angular acceleration of the load swing

FFC: Feed Forward Controller

ZV: Zero Vibration

ZVD: Zero Vibration Derivative

ZVDD: Zero Vibration Double Derivative

F: Applied Force

ABSTRACT

This research presents an efficient control scheme for a 2D Gantry Crane System incorporated with hybrid ZVDD, PID and IMC controllers. Using the system identification tool box in Matlab software, an IMC incorporated with ZVDD and PID is developed and applied to the 2D gantry crane system. The hybid PID with IMC controller is capable of controlling both the position and sway angle of the 2D Gantry Crane better than hybrid ZVDD and PID controller. The research work compares the performances of the hybrid PID with IMC controller and hybrid ZVDD and PID controllers used for the 2D Gantry Crane System control. The controlled system as examined under various test signals shows that better performance was achieved using the hybrid PID with IMC controller because of its robustness to track different input signals to the system and also when subjected to different payload masses. The hybrid ZVDD, PID and IMC Controllers require less control effort than the hybrid ZVDD and PID.

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Study Background

Crane is a machine or device used by human to help humans to move loads (payload) from one point to another. 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. Gantry crane are widely used in industries, construction or shipyards due to limited human capacity to carry the various types of load. This system is developed to load and unload heavy materials from one place to another desired location.

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 utilized these cranes in erection of tall structures for building construction.

Figure 1.1 shows a typical gantry crane.

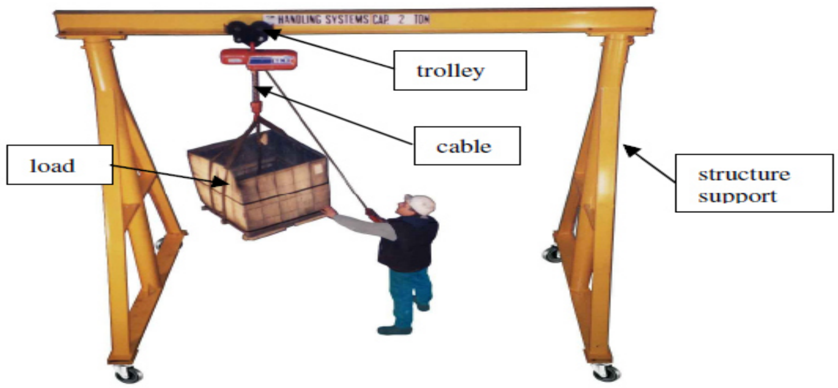


Figure 1.1 A Gantry crane system [2]

The control objective of this system is to move the trolley to a desired position as fast and accurate as possible without causing any excessive swing at the final position [3]. In transportation industry, speed is required as the priority issue as it translates into productivity and efficiency of the system [4-5]. However, controlling the crane manually by human will tend to excite sway angles of the hoisting line and degrade the overall performance of the system. At very low speed, the payload angle is not significant and can be ignored, but not for high speed condition. The sway angle becomes larger and harder to settle down during movement and unloading [6-7]. Besides, the effect of increasing the hoisting will degrade the performance of sway angle [8-9]. This is a very severe problem especially in the industries which require small of sway angle when the time taken for the transportation is short and high safety [10-11]. It is therefore of utmost importance to come up with a control system design to automate the gantry crane system in order to achieve its operating goals.

In recent years there has been a significant increase in the number of control system techniques that are based on nonlinear concepts. One of such method is the nonlinear inverse-model based control strategy. This method is however highly dependent on the availability of the inverse of the system model under control, which are normally difficult to obtain analytically for nonlinear systems. In this work, we investigate the use of hybid PID with inverse model control strategy to control the sway angle as well as the position of the gantry crane. The modeling of the control system for the purpose of this research is adopted. Also, hybrid PID with inverse model controllers will be used as a control mechanism.

Figure 1.2 shows the schematic diagram of a non-linear gantry crane system.

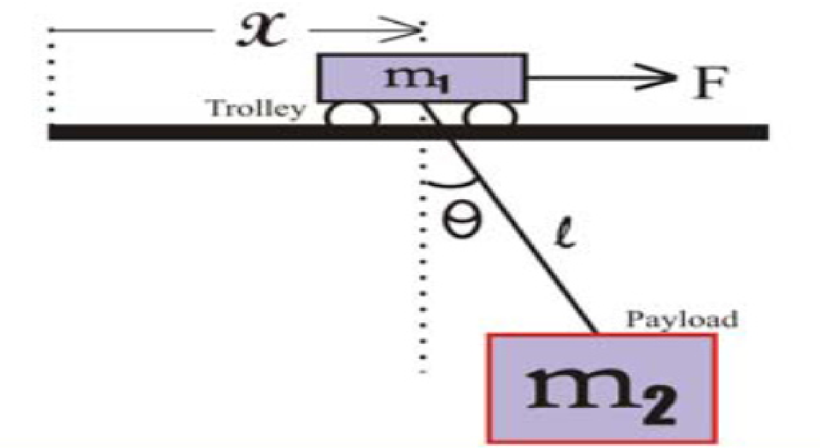


Figure.1.2 Schematic diagram of a nonlinear GCS [12]

1.2 Problem Statement

Gantry crane operation induces undesired sway due to the acceleration of an inertia payload. Once the crane has reached the desired location, oscillation in the payload remains, which can be both dangerous and inefficient. Crane operators must manually dampen sway or wait for the oscillation to naturally dampen before taking further action.

As a result of the above mentioned problems, researchers implemented many different techniques to solve these problems. Such as model predictive controllers, input shaping technique, wave based technique, PID controllers, adaptive control techniques, neural networks and fuzzy logic control algorithm etc.

In this research, hybrid PID with inverse model controller is obtained and applied to the nonlinear model of the system. MATLAB/ Simulink environment will be used for the design and implementation of this work.

1.3 Aim and Objectives

The aim of this research is to control the position and sway angle of the 2D gantry crane by using hybrid PID with inverse model controller. To achieve this aim, the following objectives are set:

1. To obtain the input-output data of the nonlinear gantry crane model using system identification toolbox in Matlab.
2. To design the inverse model controller for the gantry crane using system identification toolbox in Matlab/Simulink Environment.
3. To design the ZVDD controller for the 2D gantry crane using Matlab/Simulink Software
4. To design the PID controller for the 2D gantry crane using Matlab/Simulink Software
5. To compare the performance analysis of hybrid ZVDD and PID controller to the hybrid PID with IMC controller.

1.4 Scope of Study

The scope of study is limited to:

1. 2D nonlinear gantry crane systems.
2. The implementation of the control scheme is limited to simulation alone.

1.5 Methodology

The model of the non-linear Gantry Crane system for the purpose of this thesis is adopted (31). The input/output data of the non-linear Gantry Crane system is obtained using Matlab/Simulink software by designing the Simulink block diagram for the 2D Gantry Crane System. Each of the input and output functions exported to the Matlab/Simulink Workspace.

The Zero Vibration Double Derivative (ZVDD) controller is designed first followed by the Proportional, Integral and Derivative (PID) controller and then the Inverse Model Controller using Matlab/Simulink Software. Comparison of result of the hybrid ZVDD and PID with that of the hybrid ZVDD, PID and IMC in other to validate the result was performed.

1.6 Thesis Organization

This thesis consists of five chapters. Chapter one gives the general introduction of the 2D gantry crane system. The rest of the thesis report is organized as follows; chapter two presents the literature review of the research work, chapter three contains the design procedures of the position and sway angle control of a 2D gantry crane with hybrid ZVDD and PID and inverse model controllers. 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

This chapter consists of some past work on Gantry Crane System by different researchers. The theories of the controllers used in this research and least squares parameter estimation are also discussed.

2.2 Past Work on Gantry Crane System

In order to overcome the addressed control issues in chapter 1, many researchers have proposed solutions by developing several control schemes for a crane system. The developed control schemes can mainly be categorized into the open loop and the closed loop techniques. Besides, a controller based on a combined open loop and closed-loop technique has also been proposed. In this section, the controllers are reviewed and discussed based upon these categories in order to help human operators and to prevent cranes from tipping over.

2.2.1 *Open Loop Techniques*

The most practical and advanced crane controllers available today are controllers based on an open loop approach designed to automate and shorten the cycle time for the gantry cranes operating along a pre-defined path. The open loop approach is intended not to excite the swing motion. It is simple to implement but cannot suppress swing motion caused by external disturbance. The most widely used of the open loop control techniques is input-shaping technique. An anti-swing crane control by using input shaping has been widely implemented in the literature [13-14]. By using this technique, the system's vibration is reduced by convolving the command input signal with a sequence of impulses that have been designed based upon natural frequencies and damping ratios of the system. Although there will be effectively no residual oscillations but large transient oscillations will happen during the transportation. Besides, input-shaping techniques are limited by the facts that they are sensitive to variations in the parameter values about the nominal values and changes in the initial conditions and external disturbances and require highly accurate values of the system parameters to achieve satisfactory system response

In [15], wave-based technique was proposed in which the control mechanism, in the form of mechanical waves, was conceptualized. If the motion of the trolley is seen as launching mechanical waves into, or absorbing waves out of the system, there is a greater hope of achieving the position control and vibration absorption successfully. Here ‘waves’ are taken not so much in the usual understanding as periodic motions in space and time, but more as propagating, long-wavelength disturbances that may or may not be oscillatory in nature. Such wave-based models are closer to the physics of the problem and allow characteristic features of the system dynamics to be used positively and creatively

2.2.2 *Closed-Loop Control Schemes*

The other control scheme that has been commonly designed for a crane control system has been a feedback-loop control scheme. It was a great control scheme that enabled the crane system to adjust its performance based upon the desired output response. Feedback schemes utilise the measurement and the estimation of the system states to reduce the oscillations and to obtain an accurate positioning for the system.

A Linear Quadratic Regulator (LQR) has been used for the control of crane systems. In [16], an LQR method was applied for the anti-sway control of an overhead crane.

A parametric formula technique was used in order to solve the LQ inverse problems when finding an appropriate weighting matrix, Q but obtaining an analytical solution to the Ricatti equation is quite difficult.

As proposed in [17], a parallel distributed fuzzy LQR controller that was combined with a GA was designed for the anti-sway control of a double-pendulum type overhead crane. A fuzzy controller was used in order to minimise the upper bounds of the quadratic performance function, whereby a GA was utilised in order to only select the important rules among all of the rules generated. The simulation results showed a satisfactory and faster response.

In [18], a state feedback controller was utilised in order to achieve robustness with respect to a rope length's variation and a linear matrix inequality (LMI) approach was formulated. However, the design of a linear controlled system requires for a linearised crane system which may be insufficient in terms of the precision of the model's representative. The nonlinear factors, such as the wind, the cable length's variation, the load mass and the trolley friction of the crane system were not included. All these factors may influence and minimise the reliability and the performance of the linearised model.

A Model Predictive Control (MPC) has become one of the most popular multivariable control algorithms owing to its advantages in dealing with constraints, its capability of utilising simple models, its closed-loop stability assurance and its robustness against parametric uncertainties [19]. An enormous amount of research has been carried out and has been reported by using an MPC for controlling gantry cranes and overhead cranes [20-24]. For instance in [20] two criteria functions were considered that have indicated the tasks of positioning the cargo to a target position in a minimum transfer time and with a prevention of the cargo sway that was caused by the cargo's acceleration together with external disturbances. In order to obtain a solution for the criteria functions or the objective functions of the MPC, multi-criteria optimisation was utilised where the contribution of the individual functions was defined by its weight in order to achieve an optimum control signal.

The MPC-based schemes for a constrained under-actuated state (the swing angle) were also presented in recent papers [25, 26]. The optimum methods for an MPC controller have depended upon the desired criterion function that was selected by the designer. Most of the research for MPC controller designs has mainly focused on the position control and a sway angle reduction. The work in [27] implemented the MPC to improve robustness and to control the induced payload swing of a shipboard crane. The algorithm was combined with a feedforward control to minimise the displacement of the load in a horizontal direction.

The work in [28] has proposed a combination of an NN and an SMC, in order to achieve a precise trolley position and to eliminate the payload sway angles. An SMC has been used as a self-tuning algorithm for the purpose of tuning the proposed NN parameters. In [29], an NN controller was proposed with an evolutionary computational training that was able to control the load swing in both the circumferential and the radial directions, concurrently. Moreover, the proposed algorithm was effective and simpler to realise than a conventional controller.

The work in [30] presented a partial feedback linearization (PFL) and adaptive sliding mode control (SMC) for sway suppression of a rotary crane in a situation of inaccurate model or poor parameter representation. Though it is simple to design and implement, PFL is highly affected by parameter variations. More so, in [31] an investigations into the development of hybrid input-shaping and PID control schemes for active sway control of a gantry crane system was proposed. Positive input shaping technique was applied in order to reduce the sway by creating a common signal that cancels its own vibration and used as a feed-forward control which is for controlling the sway angle of the pendulum, while the proportional integral derivative (PID) controller is used as a feedback control which is for controlling the crane position. The PID controller was tuned using Ziegler-Nichols method to get the best performance of the system. The hybrid input-shaping and PID control schemes guarantee a fast input tracking capability, precise payload positioning and very minimal sway motion. The modeling of gantry crane is used to simulate the system using MATLAB/SIMULINK software. The results of the response with the controllers were presented in time domains and frequency domains.

2.3 Theory of The Controllers

In this research, ZVDD, PID and Inverse Model Controllers are designed. The combination of these controllers gives better simulation result when compared to hybrid ZVDD and PID Controllers.

2.3.1 *Input Shaping Techniques*

Input Shaping techniques have been utilized to generate low vibration commands for flexible systems such as robot manipulators, industrial cranes and many types of automated machinery. Input shaping is a notch filtering technique whereby a specially designed sequence of impulses known as the input shaper is convolved with a reference command thereby resulting to a new form of command that causes little or no residual vibration. By using these techniques, the system's vibration is reduced by convolving the command input signal with a sequence of impulses that have been designed based upon natural frequencies and damping ratios of the system. Figure 2.1

(a) shows the ZV shaper implementation by convolving sequence of two impulses with the desired system command.

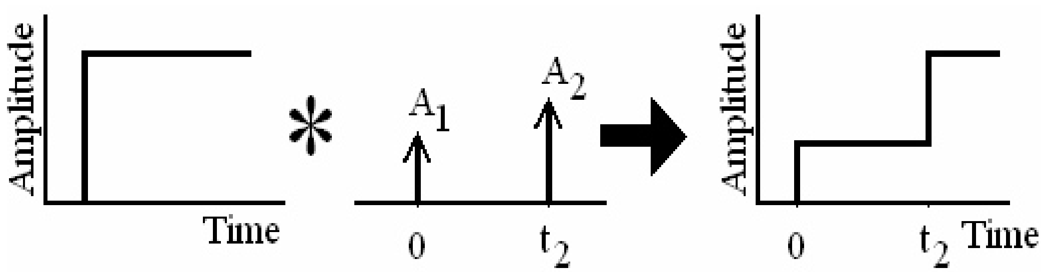


Figure.2.1 (a) ZV shaper

Robustness can be improved by increasing the number of impulses. Adding an impulse to ZV produces TS shaper.

Implementation of the ZVD shaper is shown in figure 2.1 (b)

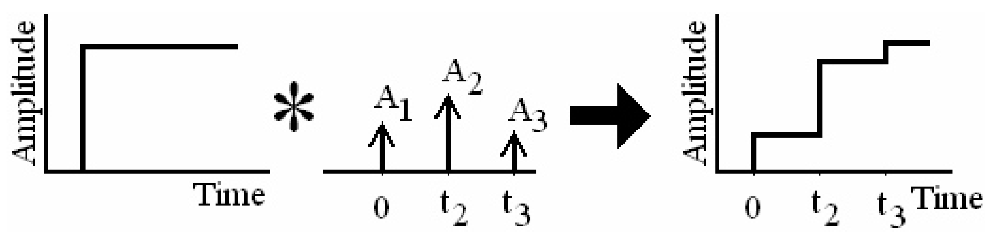


Figure.2.1 (b) ZVD Shaper

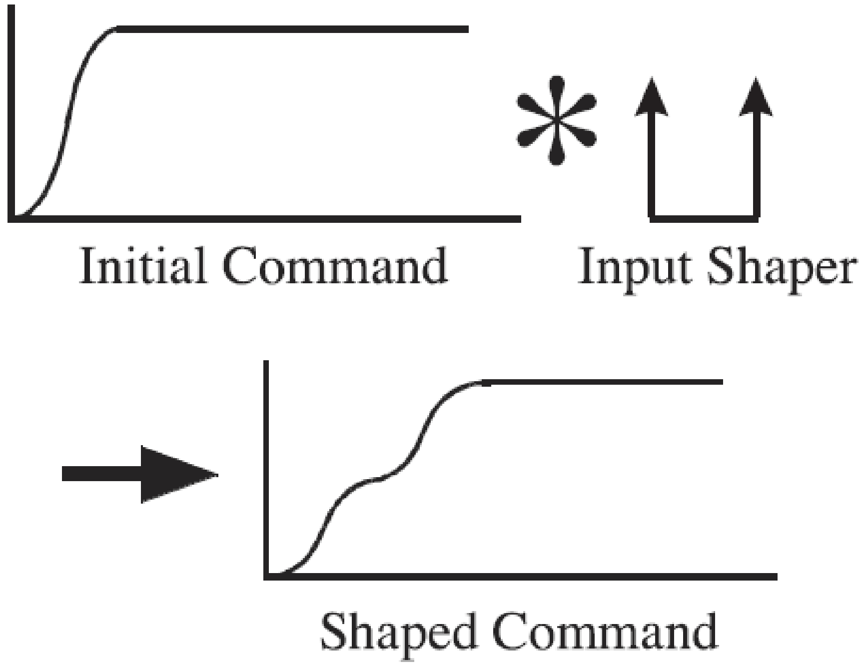


Figure.2.1 (c) Input Shaping Processes [32]

Table 2.1 shows summarized of positive input shaping techniques

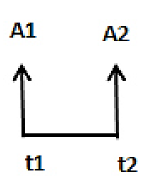
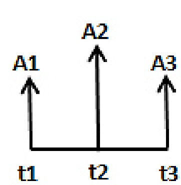
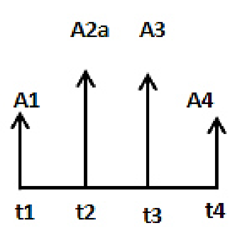
Positive Zero Sway (PZS)	Positive Zero Sway Derivative (PZSD)	Positive Zero Sway Derivative-Derivative (PZSDD)
• Contain 2 impulse response include: i. Unity amplitude summation ii. Time optimality constraints 	• Contain 3 impulse response include: i. Unity amplitude summation ii. Time optimality constraints iii. First order robustness constraint equation. 	• Contain 3 impulse response include: i. Unity amplitude summation ii. Time optimality constraints iii. Second order robustness constraint equation. 

Table 2.1 Positive Input Shaping Techniques.

2.3.2 *PID Control Scheme*

In this section, PID control is presented. Proportional, Integral and Derivative (PID) control is the most popular feedback controller used within the process industries involved in controlling the crane position. PID also provides a constant system output at a specified set point. The desired closed loop dynamics is obtained by adjusting the three parameters such as Proportional gain (K_p), Integral time (*Ti*) and Derivative time (*Td*), often iteratively by "tuning" and without specific knowledge of a plant model. The general representation of PID is given as

$$U(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d d \frac{e(t)}{dt} \right] \quad (2.1)$$

$$C(S) = K_P + K_I \frac{1}{S} + K_D S \quad (2.2)$$

Where $U(t)$ is the control signal, K_P, K_I and K_D are respectively the proportional, integral and derivative gains. *e(t)* is the error calculated by taking the difference between the actual signal and the output response. PID can be tuned manually or automatically to meet the desired response based on the three available features. The proportional gain is responsible for the system response. However, faster response leads to steady state error. The integral gain takes care of the steady error. The derivative feature reduces overshoot. Thus, if those features are not tuned properly, it may affect the closed loop stability of the system. The block diagram of a PID control scheme is shown in Figure 2.2. The signal is applied to the gantry crane. The resulting responses will be feedback for comparison with the reference input. The controller is tuned to make this error zero.

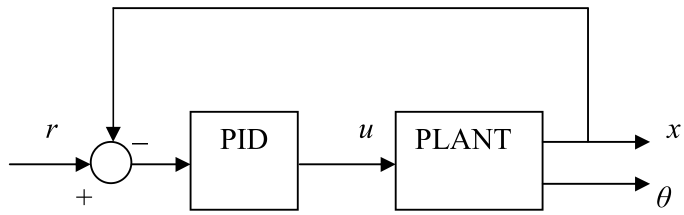


Figure 2.2 The PID controller structure

2.3.3. *Inverse Model Controller*

Inversion of system dynamics is a widely investigated approach used to design the FFC to obtain precision tracking of output trajectories through a combination of feed-forward and state feedback controllers. Inverse dynamic analysis reverses the process by taking the system output function as input to the plant and taking the system input function as output to the plant. Figure 2.3 and Figure 2.4 Shows the System identification block diagram of getting IMC and hybrid ZVDD, PID and IMC respectively.

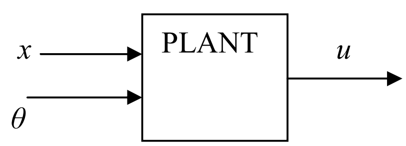


Figure 2.3: System Identification Block Diagram to Obtain IMC

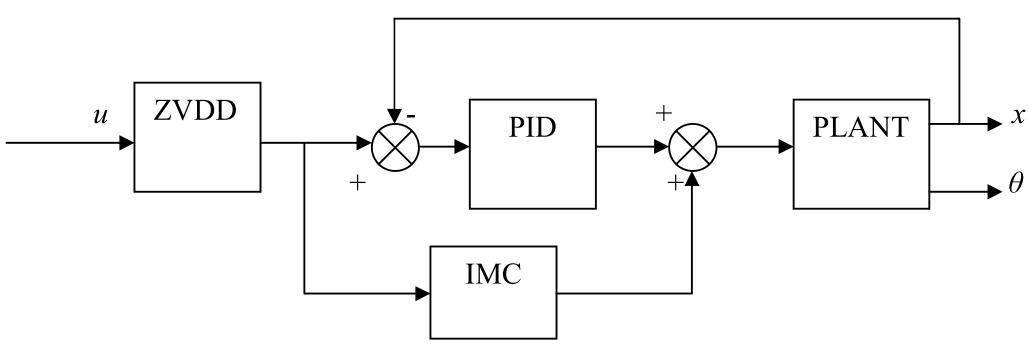


Figure.2.4 Hybrid ZVDD, PID and IMC

2.4 Least-Square (Ls) Parameter Estimation

Least squares (LS) parameter estimator is one of the most popular estimation algorithms. It forms the basis of other more complicated estimation algorithms. Karl Friedrich Gauss first formulated the least squares estimation method in 1795 for astronomical computation purposes [33]. Various other methods are also available such as Bayesian method and maximum likelihood method. All these methods are based on minimizing certain cost functions.

The discrete time (D-T) least squares is a basic technique for parameter estimation. Before this method is described, some of the important notations are defined.

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

$\varepsilon(k)$ = $y(k) - \hat{y}(k)$ = residual

$\hat{y}(k)$ = estimated output signal

In general, this method finds the 'most probable' value of $\underline{\theta}$, denoted by $\hat{\underline{\theta}}$, such that it minimizes the sum of the squares of the residual, $\boldsymbol{\varepsilon}$, which will be explained in greater details in the following sections.

There are 2 ways of estimating parameters using the LS algorithm namely, Offline LS Estimation (Batch Processing) and Online LS Estimation (Recursive Least Squares – RLS).

2.4.1 *Offline/Batch Least-Squares Estimation*

Offline LS estimation can be used to estimate system parameters when at least a set of input data into the system and a set of the corresponding output data are available.

Consider the D-T transfer function

$$\frac{y(k)}{u(k)} = \frac{b_0 + b_1 z^{-1} + \cdots b_{Nb} z^{-Nb}}{1 - a_1 z^{-1} - a_2 z^{-2} - \cdots a_{Na} z^{-Na}} \quad (2.3)$$

That can be written as

$$y(k) = a_1 y(k-1) + a_2 y(k-2) + \cdots a_{N_a} y(k - N_a) + b_0 u(k) + b_1 u(k-1) + \cdots b_{N_b} u(k - N_b$$

(2.4a)

Equation (2.4b) is then arranged in regression equation form as follows

$$y(k) - \underbrace{[\,y(k-1) \;\cdots\; y(k-N_a) \;\; u(k) \;\cdots\; u(k-N_b)\,]}_{\varphi^T(k)} \underbrace{\begin{bmatrix} a_1 \\ \vdots \\ a_{N_a} \\ b_1 \\ \vdots \\ b_{N_b} \end{bmatrix}}_{\underline{\theta}}$$

$$= \varphi^T(k)\theta$$

$$= \hat{y}(k) \tag{2.4b}$$

$\underline{\theta}(k)$ is determined such that the output calculated from the right hand side of Equation (2.4), which is $\hat{y}(k) = \varphi^T(k)\underline{\theta}$, matches as closely as possible with the measured $y(k)$in the sense of least squares. This is done by minimizing

$$J = \frac{1}{2}\sum_{k=1}^{N}[\varepsilon(k)]^2$$

$$= \frac{1}{2}\sum_{k=1}^{N}\left[y(k) - \varphi^T(k)\underline{\theta}\right]^2$$

$$J = \frac{1}{2}\mathrm{E}(N)^{\mathrm{T}}\mathrm{E}(N) \tag{2.5}$$

Where,

N = total number of data available for estimation

$\mathrm{E}(N) = \mathrm{Y}(N) - \hat{\mathrm{Y}}(N)\ldots$

$$= Y(N) - \Phi(N)\underline{\theta}$$

$$= [\varepsilon(1)\ \ \varepsilon(2)\ \ \cdots\ \ \varepsilon(N)]$$

$$Y(N)^T = [\ y(1)\ \ y(2) \cdots\ y(N)\ ]$$

$$\Phi(N) = \begin{bmatrix} \varphi^T(1) \\ \varphi^T(2) \\ \vdots \\ \varphi^T(N) \end{bmatrix}$$

J in Equation (2.5) is minimized by expanding the quadratic function, finding its derivative and equating it to zero to find the minimum point,

$$\frac{\partial J}{\partial \theta} = -\Phi^T(Y - \Phi\theta) = 0$$

giving,

$$\underline{\hat{\theta}} = [\Phi(N)^T\ \Phi(N)]^{-1}\ \Phi(N)^T Y(N) \qquad (2.6)$$

Where $\underline{\hat{\theta}}$ is unique if $[\Phi(N)^T\ \Phi(N)]$ is non-singular. Equation (2.6) is the equation used to find the estimated parameters for batch processing of LS method. The method can be used to find the relationship between two variables of both linear and nonlinear systems. The following examples show how the LS method is used.

Example 2.1

Given that a process model of the form $y(k) = \frac{bz^{-1}}{1+az^{-1}}u(k)$ with the input-output experimental data at different time instant $k, \{u(k), y(k)\}$, given in Table 2.2 below

Table 2.2 input and output data for example

K	1	2	3	4
u(k)	1	-1	-1	1
y(k)	12	4	-12	-4

Assuming that $u(k \leq 0) = 0$ and $y(k \leq 0) = 0$, the unknown parameters, a and b, can be estimated using the simple least squares method.

First the plant model can be written in the form that uses the backward shift operator as follows:

$$y(k) = \frac{bz^{-1}}{1+az^{-1}}u(k)$$

$$y(k)(1 + az^{-1}) = bz^{-1}u(k)$$

$$y(k) + ay(k-1) = bu(k-1)$$

$$y(k) = -ay(k-1) + bu(k-1)$$

Writing in the regression form,

$$y(k) = \underbrace{[-y(k-1) \quad u(k-1)]}_{\varphi^T(k)} \underbrace{\begin{bmatrix} a \\ b \end{bmatrix}}_{\theta}$$

The estimates using the least squares method is obtained as

$$\hat{\theta} = [\Phi^T(N)\Phi(N)]^{-1}\, \Phi^T(N)Y(N)$$

where,

$$Y^T(N) = Y^T(4) = [y(1) \;\; y(2) \;\; y(3) \;\; y(4)] = [12 \;\; 4 \; -12 \; -4]$$

$$\Phi(\mathrm{N}) = \Phi(4) = \begin{bmatrix} \varphi^T(1) \\ \varphi^T(2) \\ \varphi^T(3) \\ \varphi^T(4) \end{bmatrix} = \begin{bmatrix} y(0) & u(0) \\ -y(1) & u(1) \\ -y(2) & u(2) \\ -y(3) & u(3) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ -12 & 1 \\ -4 & -1 \\ 12 & -1 \end{bmatrix}$$

Therefore, $\hat{\theta} = \begin{bmatrix} 0.5 \\ 10 \end{bmatrix}$

Giving, $y(k) - \frac{10z^{-1}}{1+0.5z^{-1}} u(k)$ where 0.5 and 10 are the estimated values of a and b respectively.

MATLAB has a System Identification Toolbox that can do the offline estimation process by providing the set of input-output data. Users can specify the type of model and method to be used.

2.5 Conclusion

This chapter summarised brief literature review of the past work carried out by researchers in controlling the position and sway angle of a 2D gantry Crane system control. Also, the theories of the controller and least-square parameter estimation were discussed. The next chapter will present the hybrid ZVDD, PID and Inverse Model Controller design.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

In this chapter, the model of 2D Gantry Crane System will be presented. Firstly, the ZVDD controller will be designed followed by PID controller and the Inverse Model controller for the position and sway angle control of 2D Gantry Crane system.

3.2 2D Gantry Crane Model

From figure 3.1, 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, the force that has been applied on the cart is F, the mass of the cart is m_1, the mass of load is m_2, the length of the bar is l, and the angle between the bar and vertical axis is θ.

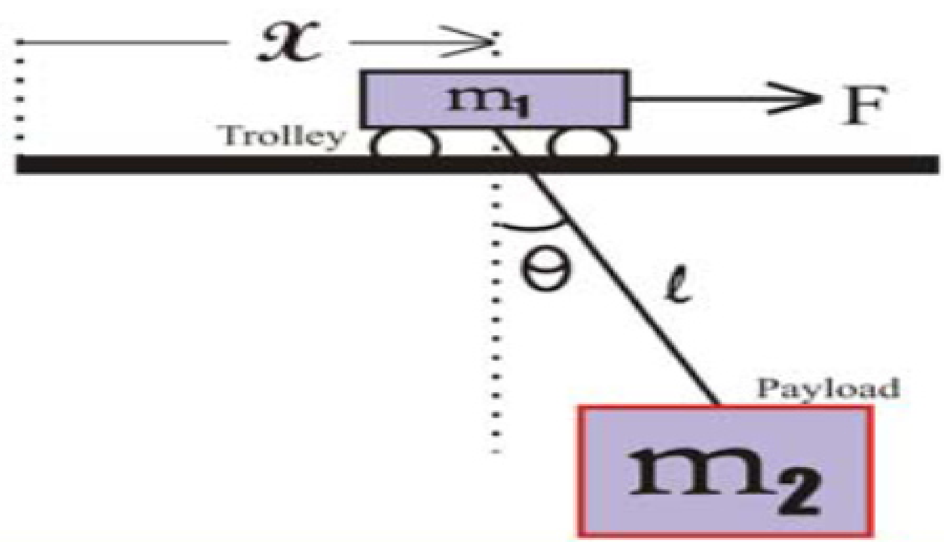


Figure 3.1 Gantry Crane Model

The mathematical models for both the acceleration of trolley and angular acceleration of the load swing in non-linear form adopted for the purpose of this thesis are represented as shown in Eq 3.1 and 3.2 respectively.

$$\ddot{x} = \frac{(F_x - m_2 l\ddot{\theta}\cos\theta + (m_2 l\dot{\theta}\sin\theta)\dot{\theta})}{(m_1 + m_2)} \tag{3.1}$$

$$\ddot{\theta} = \frac{((-g\sin\theta) - \ddot{x}\cos\theta)}{l} \tag{3.2}$$

Eq. (3.1) and (3.2) are the two equations used for the controller design. Where

m_1: mass of the trolley (kg)

m_2: mass of the payload (kg)

l: Length of rope (m)

g: Gravity acceleration (m/s²)

θ: Angle of load swing (rad)

$\ddot{x}$: Acceleration of trolley (m/s²)

$\ddot{\theta}$: Angular acceleration of the load swing (rad/s²)

Table 3.1 Estimated parameters of the 2D Gantry Crane System

Parameter (s)	**Symbol (s)**	**Value (s)**	**Unit (s)**
Mass of the cart	m_1	2	Kg
Length of the bar	l	0.64	m
Acceleration due to gravity	g	9.81	m/s^2

3.3 Controllers

3.3.1 *Input Shaping Control Scheme*

The design objective of input shaping is to determine the amplitude and time locations of the impulses in order to reduce the detrimental effects of system flexibility. Using Curve fitting toolbox in the MATLAB software to determine the damping ratio and natural frequency of the system, with the input and output data obtained from the nonlinear crane system. These parameters are obtained from the natural frequencies and damping ratios of the system. The corresponding design relations for achieving a zero residual single-mode sway of a system and to ensure that the shaped command input produces the same rigid body motion as the unshaped command yields a four-impulse sequence namely zero vibration derivative-derivative (ZVDD) with parameter as shown in Eq. (3.3).

$t_1 = 0,\ t_2 = \frac{\pi}{w_d}, t_3 = \frac{2\pi}{w_d},\ t_4 = \frac{3\pi}{w_d}$

$$A_1 = \frac{1}{1 + 3K + 3K^2 + K^3} \tag{3.3}$$

$$A_2 = \frac{3K}{1 + 3K + 3K^2 + K^3} \tag{3.4}$$

$$A_3 = \frac{3K^2}{1 + 3K + 3K^2 + K^3} \tag{3.5}$$

$$A_4 = \frac{K^3}{1 + 3K + 3K^2 + K^3} \tag{3.6}$$

Where

$$K = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{3.7}$$

$$w_d = w_n\sqrt{1 - \zeta^2} \tag{3.8}$$

w_n= natural frequency, ζ = damping ratio.

Table 3.2 Estimated parameters of the Input Shaper

Amplitude(m)		**Time(s)**	
Parameter	**Value**	**Parameter**	**Value**
A_1	0.1280	t_1	0
A_2	0.3790	t_2	0.6909
A_3	0.3694	t_3	1.3817
A_4	0.1236	t_4	2.0726

3.3.2 *PID Control Scheme*

The Proportional, Integral and Derivative (PID) controller of this work was designed using auto tuning method to obtain the various gain values of the proportional, integral and derivative. The time domain equation and general transfer function of PID controller are given as in Eq. (3.9) and (3.10)

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

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

Where K_I, K_P and K_D are the proportional gain, integral gain and derivative gain respectively.

Figure 3.2 shows the PID controller structure.

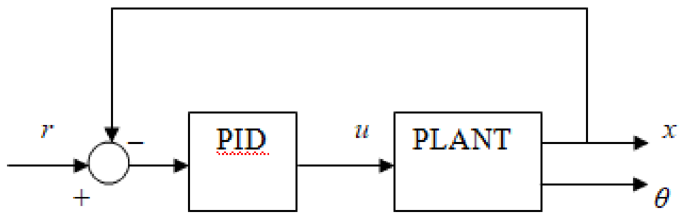


Figure 3.2 The PID controller structure

The values of the PID controller used in the design gotten using auto tuning method in Matlab/Simulink Software are as follows:

$K_p = 1, K_i = 0.1, K_d = 3$

3.3.3 Inverse Model Controller

Inverse dynamic analysis reverses the process by taking the system output function as input to the plant and taking the system input function as output to the plant. This was done using system identification tool box in MATLAB. Steps taken in designing the IMC controller are stated below: The simulink block diagram is run and the input/output data are exported to Matlab command window. Figure 3.3 shows the Simulink block diagram of Nonlinear Gantry Crane

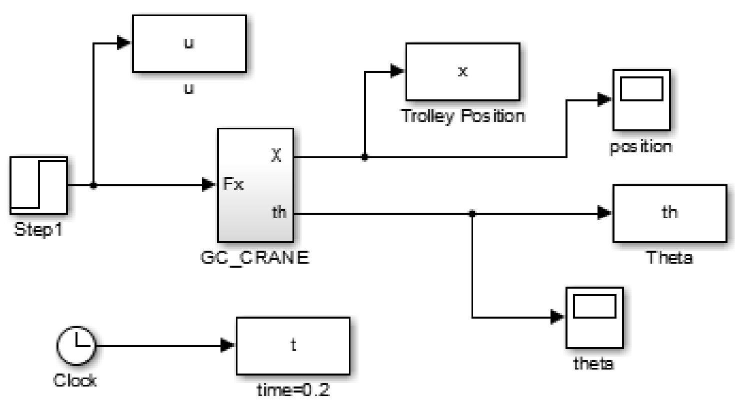


Figure 3.3 Simulink block diagram of Nonlinear Gantry Crane System

Also from the Matlab command window, system identification toolbox is launched as shown in Figure 3.4

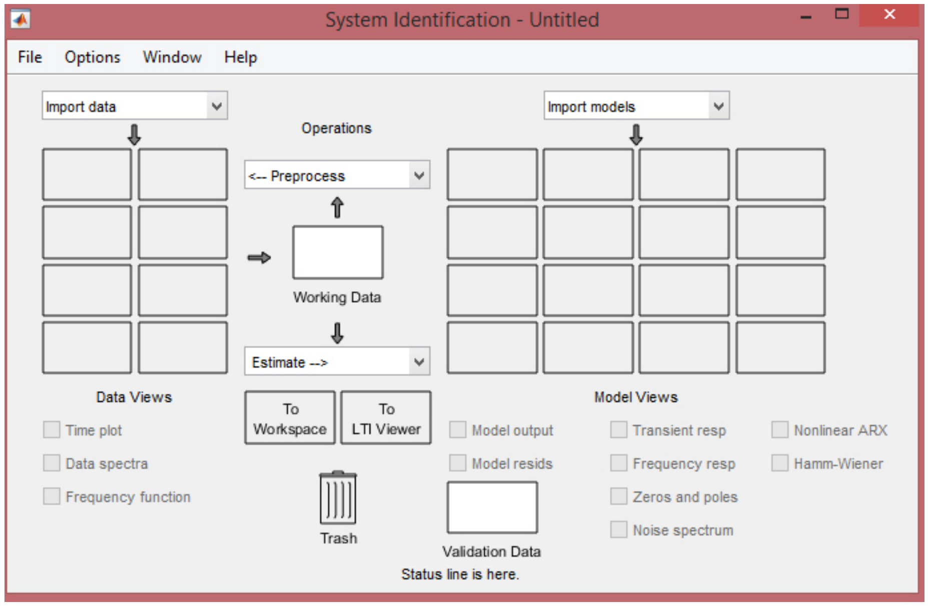


Figure 3.4 System Identification toolbox

Input/Output data is imported from the Matlab command window through time domain data by interchanging the input and output variable as shown in Figure 3.5

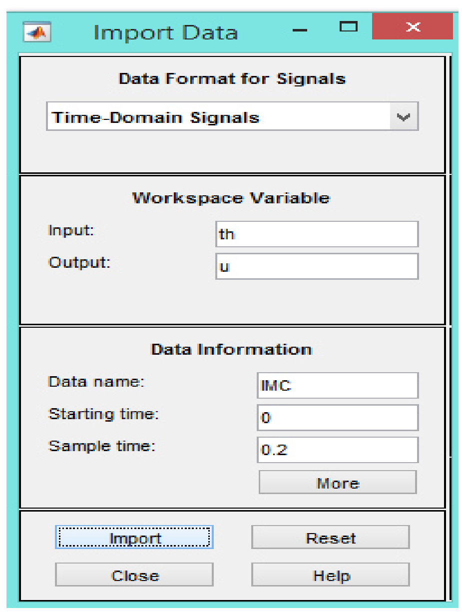


Figure 3.5 Input/Output data interchanged

The working data which is the imported data is run to get the IMC transfer function of the 2D gantry Crane after analysing the response as shown in Figure 3.6 and Figure 3.7

Command Window

New to MATLAB? See resources for Getting Started.

Iteration	Cost	Norm of step	First-order optimality	Improvement (%) Expected	Improvement (%) Achieved	Bisections
0	3.72901	-	0.0946	26.7	-	-
1	1.00701	1.55e+04	1.45e+03	26.7	73	2
2	0.310156	6.83e+03	8.13e+03	97.1	69.2	0
3	0.0909777	1.11e+04	2.5e+05	299	70.7	0
4	0.0671075	1.7e+04	3.07e+05	903	26.2	5
5	0.0510102	2.88e+03	3.32e+05	1.04e+03	24	2
6	0.0474783	3.94e+03	1.95e+05	1.16e+03	6.92	2
7	0.0239592	3.57e+03	1.42e+05	1.2e+03	49.5	1
8	0.0207166	2.75e+03	6.4e+04	692	13.5	0
9	0.0202081	3.6e+03	6.73e+04	168	2.45	3
10	0.0200705	893	2.73e+03	55.5	0.681	0
11	0.020067	283	638	29.3	0.0177	0
12	0.0200669	41.1	643	29.8	0.000593	0
13	0.0200669	26	48.3	30.1	3.48e-05	0
14	0.0200669	3.5	64.5	30.2	3.34e-06	0
15	0.0200669	2.58	4.57	30.3	3.29e-07	0
16	0.0200669	0.314	6.57	30.3	3.17e-08	0
17	0.0200669	0.258	0.437	30.3	3.16e-09	0
18	0.0200669	0.0279	0.673	30.3	3.04e-10	0
19	0.0200669	0.0258	0.0418	30.3	3.04e-11	0
20	0.0200669	0.00245	0.0691	30.3	2.97e-12	0

Figure 3.6 IMC Transfer Function Iteration Process

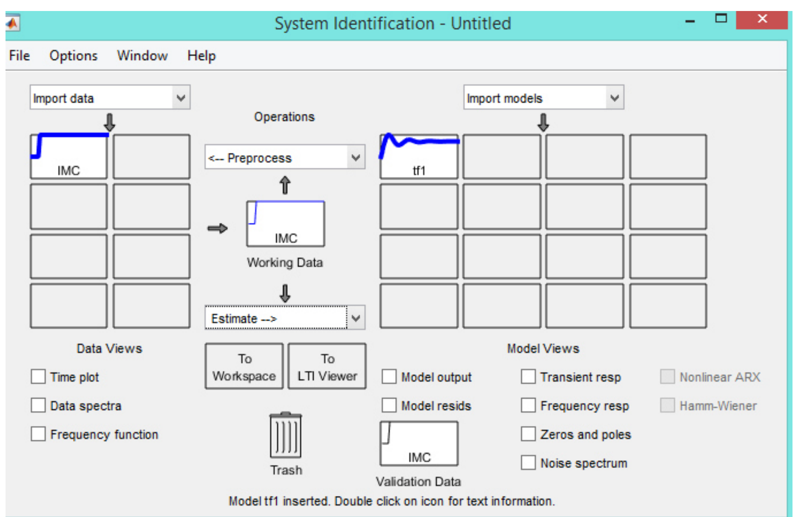


Figure 3.7 IMC transfer function identification Process

Eq. (3.12) shows the inverse model transfer function of the plant after running the system identification Simulink block diagram using MATLAB software

$$T_f = \frac{-1.273s^2 - 1.254e04s - 4481}{s^3 + 21.3s^2 + 959.9s + 1.046e04} \tag{3.12}$$

3.4 Simulation Diagram

Figure 3.8 shows the Simulink block diagram for position and sway angle control of 2D Gantry Crane System with ZVDD, PID and inverse model controllers. From the Simulink model, it can be seen that the system is a single input and multiple output (SIMO). The set up combined both three types of controllers with a manual switch as selector at the input for selecting a test signal. The 2D Gantry Crane model block used was a nonlinear block (that is nonlinear equation describing the plant).

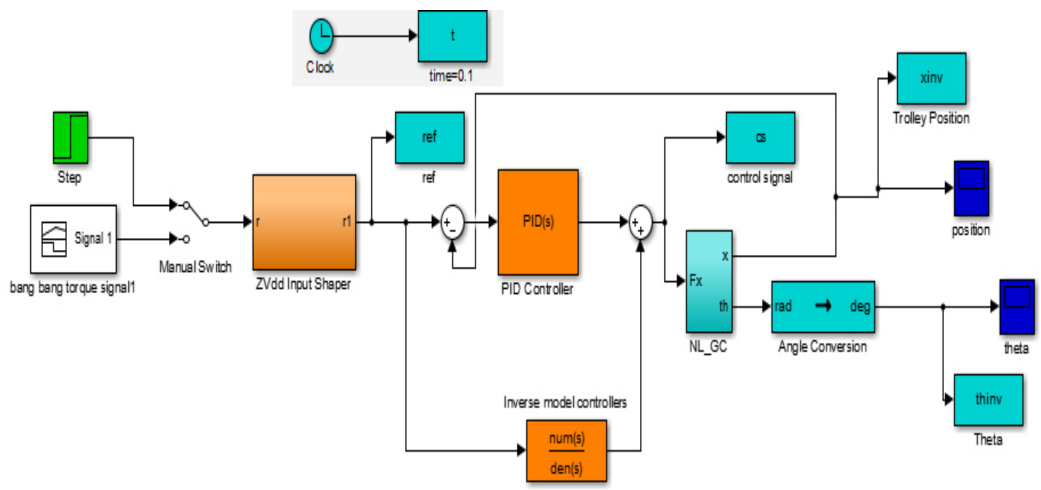


Figure 3.8 Simulink Block Diagram with ZVDD, PID and IMC

3.5 Conclusion

This chapter presented design procedures of ZVDD, PID and IMC controllers. The hybrid 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

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, simulation results for position and sway angle control for a 2D gantry crane system (GCS) are presented and discussed. This is done with the creation of a controller that combines the characteristics of ZVDD, PID and IMC to get a better response. The results obtained for both the hybrid ZVDD and PID controllers with that of the hybrid ZVDD, PID and IMC controllers were presented and compared under test signals of step response and bang bang signal.

4.2 Step Response With Parameter Variation

A step signal was set as input to the system with ZVDD, PID and IMC Controllers with varying payload masses.

4.2.1 *When m_2=0.5Kg*

Figure 4.1, 4.2 and 4.3 shows the various controllers step responses for the position, sway angle and control signal of the system when the payload mass m_2=0.5.

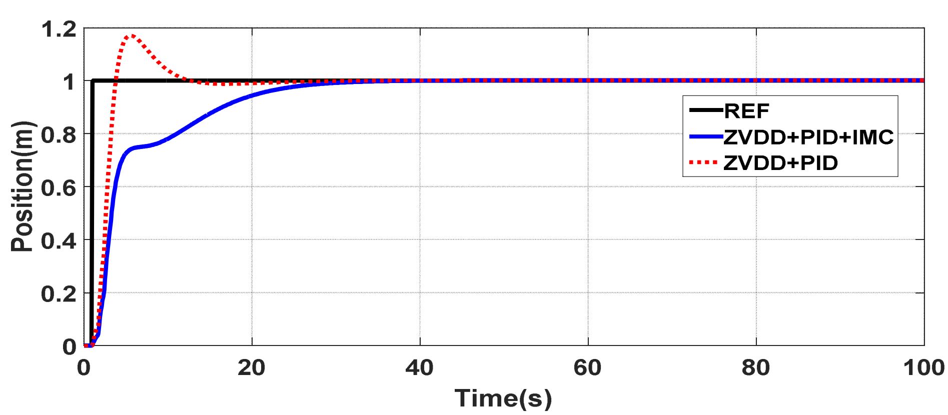


Figure 4.1 Position of the controller when m_2=0.5Kg

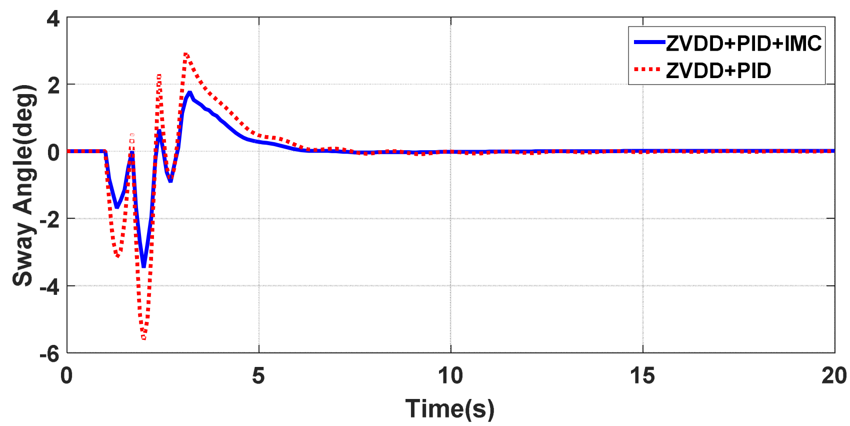


Figure 4.2 Sway Angle of the controller when m_2=0.5Kg

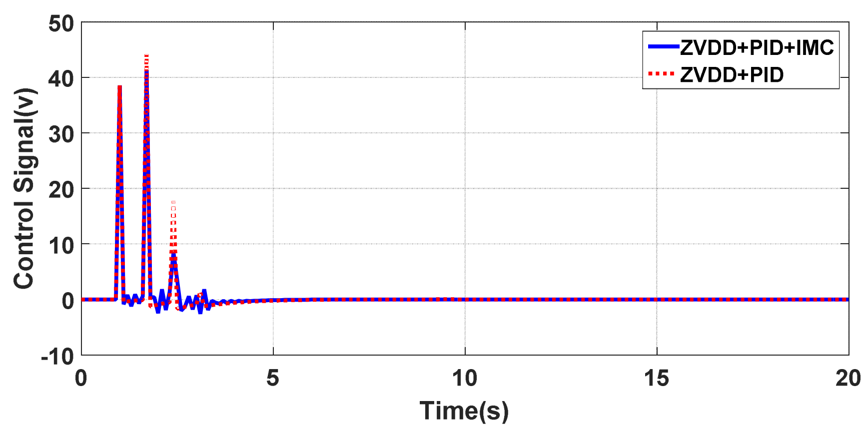


Figure 4.3 Control Signal of the controllers when m_2=0.5Kg

The summary of the above step responses for the position, sway angle and control signal can be seen in Table 4.1 below

Table 4.1 Summary of performance measures of GCS step responses when m_2=0.5Kg

Controllers	Settling Time(s)	Overshoot	Maximum Control Signal (v)	Maximum Sway Angle (deg)
ZVDD+PID	20	1.17	44	2.95
ZVDD+PID+IMC	30	0	41	1.77

As can be seen from table 4.1, the hybrid ZVDD and PID has high overshoot but settles faster when compared to the hybrid ZVDD, PID and IMC controllers having no overshoot..The control effort of the hybrid ZVDD, PID and IMC Controllers is lesser when compared to the hybrid ZVDD and PID Controllers.

4.2.2 ***When m_2=0.3Kg***

Figure 4.4, 4.5 and 4.6 shows the various controllers step responses for the position, sway angle and control signal of the system when the payload mass m_2=0.3Kg

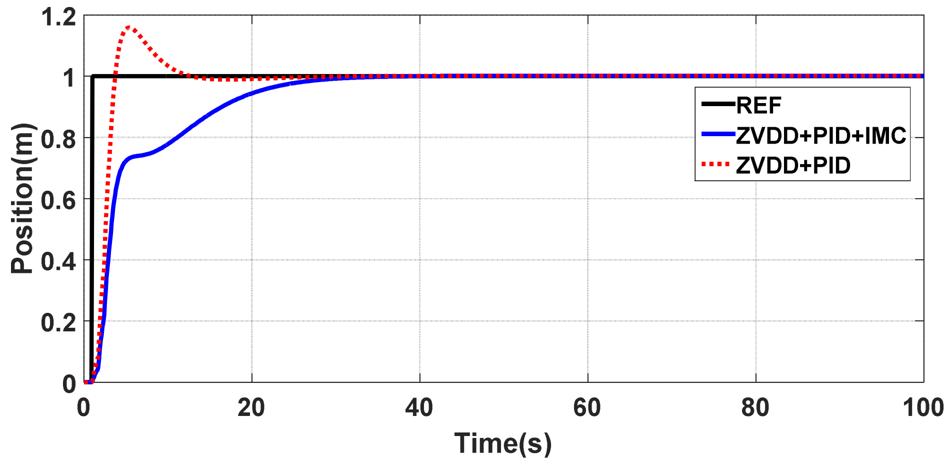


Figure 4.4 Position of the controller when m_2=0.3Kg

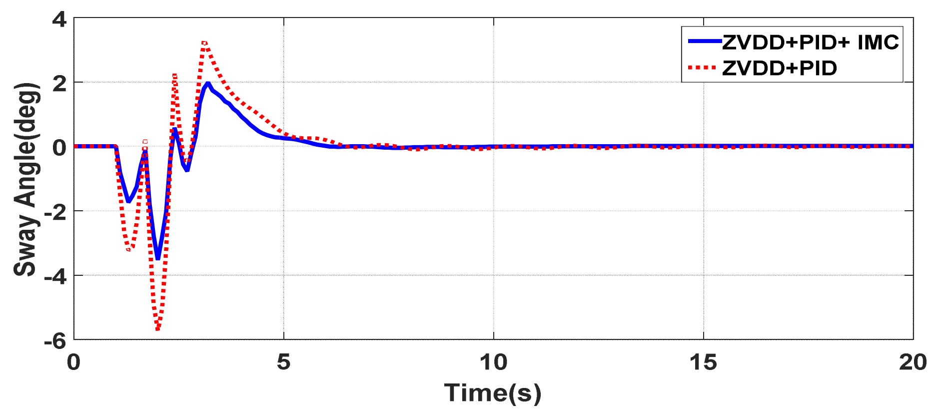


Figure 4.5 Sway Angle of the controller when m_2=0.3Kg

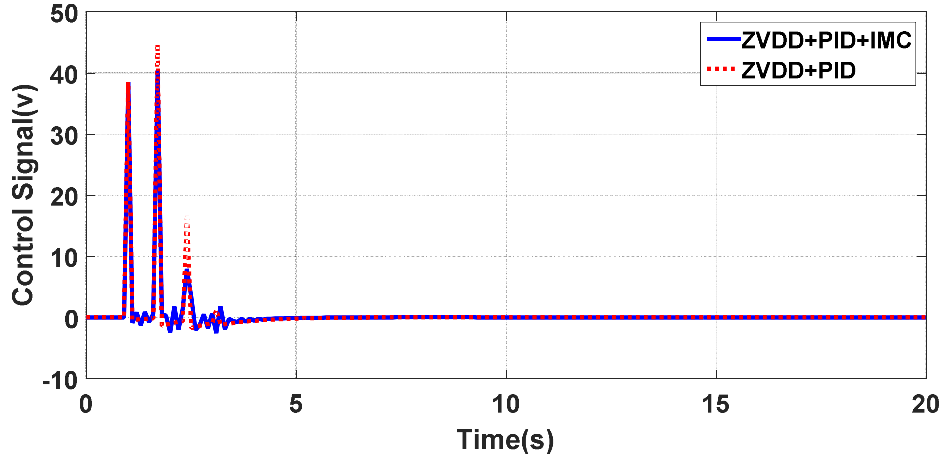


Figure 4.6 Control Signal of the controllers when m_2=0.3Kg

The summary of the above step responses for the position, sway angle and control signal can be seen in Table 4.2

Table 4.2 Summary of performance measures of GCS step responses when m2=0.3Kg

Controllers	**Settling Time(s)**	**Overshoot**	**Maximum Control Signal (v)**	**Maximum Sway Angle (deg)**
ZVDD+PID	22	1.17	44	3.3
ZVDD+PID+IMC	30	0	41	2

As can be seen from table 4.2, the hybrid ZVDD and PID has high overshoot while the ZVDD, PID and IMC controllers has none.

4.2.3 *When m_2=0.1Kg*

Figure 4.7, 4.8 and 4.9 shows the various controllers step responses for the position, sway angle and control signal of the system when the payload mass m_2=0.1Kg.

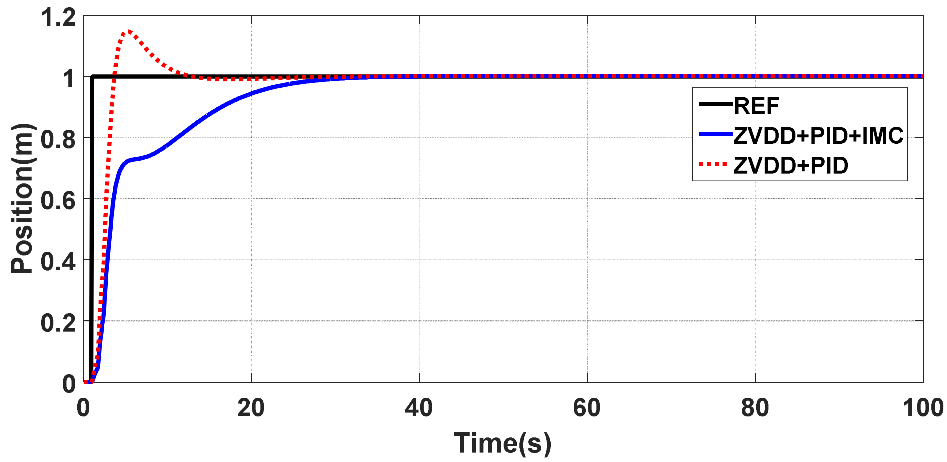


Figure 4.7 Position of the controller when m_2=0.1Kg

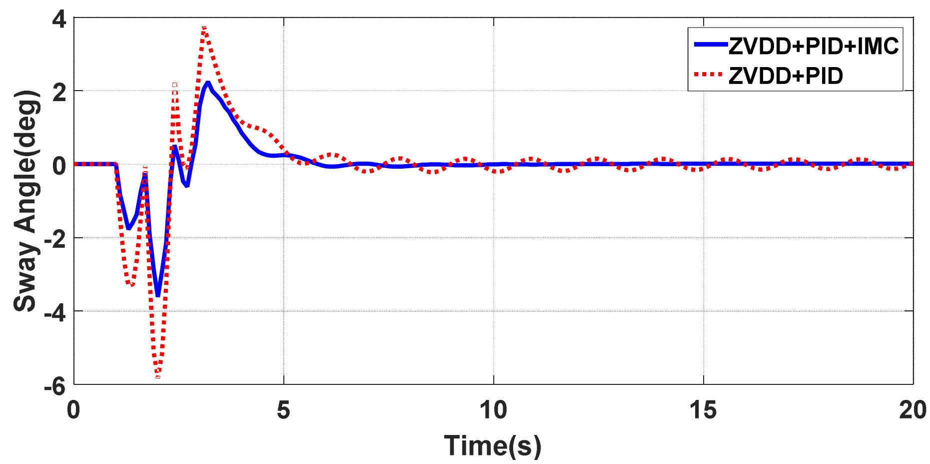


Figure 4.8 Sway Angle of the controller when m_2=0.1Kg

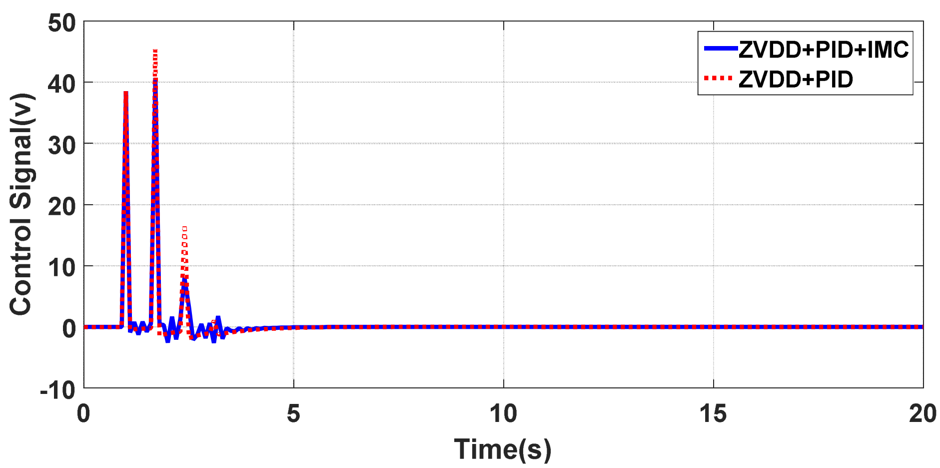


Figure 4.9 Control Signal of the controllers when m_2=0.1Kg

The summary of the above step responses for the position, sway angle and control signal can be seen in Table 4.5 and 4.6 below

Table 4.3 Summary of performance measures of GCS step responses when m_2=0.1Kg

Controllers	**Settling Time(s)**	**Overshoot**	**Maximum Control Signal (v)**	**Maximum Sway Angle (deg)**
ZVDD+PID	21	1.17	44	3.75
ZVDD+PID+IMC	22	0	41	2.25

As can be seen from table 4.3, the hybrid ZVDD and PID has high overshoot while the hybrid ZVDD, PID and IMC controllers has none.

4.3 Bang Bang Response With Parameter Variation

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 under varying payload masses.

4.3.1 *When m_2= 0.5Kg*

Figure 4.10, 4.11 and 4.12 shows the various controllers bang bang responses for the position, sway angle and control signal of the system when the payload mass m_2=0.5.

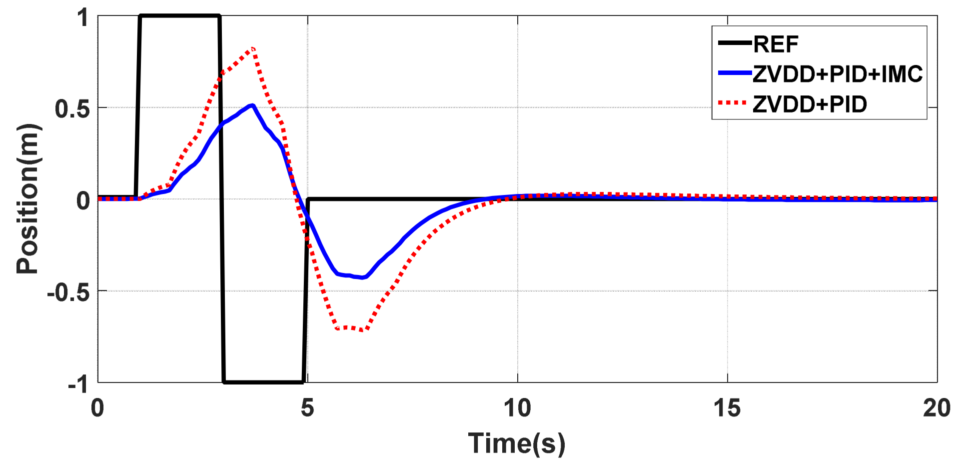


Figure 4.10 Position Bang-Bang response of the controller when m_2=0.5Kg

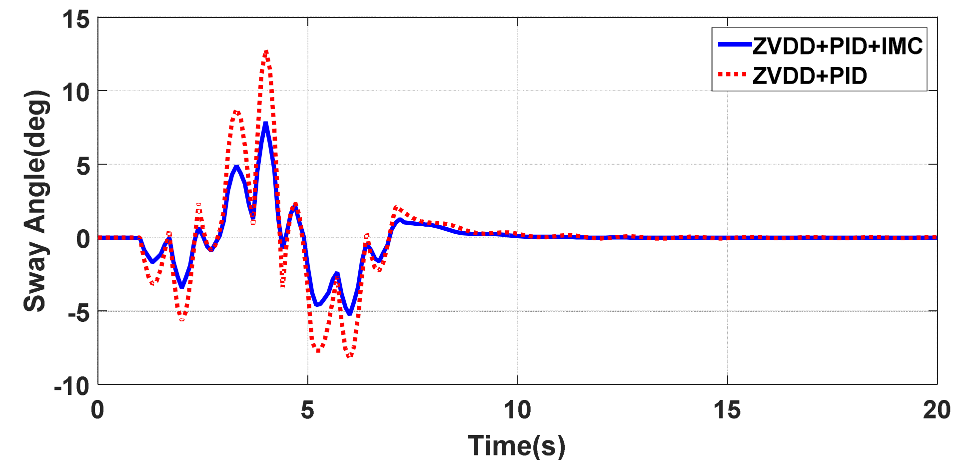


Figure 4.11 Sway Angle Bang Bang response of the controller when m_2=0.5Kg

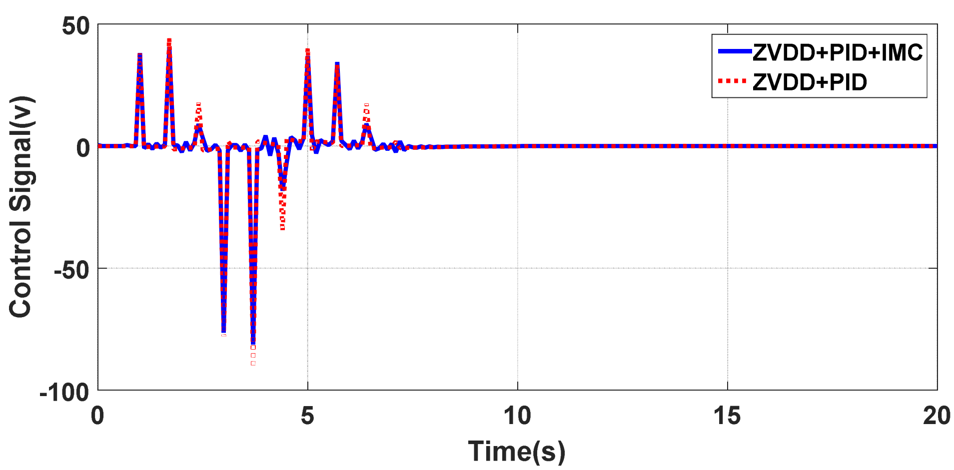


Figure 4.12 Control Signal Bang Bang responses of the controllers when m_2=0.5Kg

The summary of the above bang bang responses for the position, sway angle and control signal can be seen in Table 4.4

Table 4.4 Summary of performance measures of GCS bang bang responses when m_2=0.5Kg

Controllers	**Maximum Control Signal (N)**	**Maximum Sway Reached (deg)**
ZVDD+PID	44	12.7
ZVDD+PID+IMC	40.5	7.9

As can be seen from Table 4.4, the hybrid ZVDD and PID have both maximum control signal and maximum sway of 44N and 12.7º respectively while that of the hybrid ZVDD, PID and IMC controllerS has both maximum control signal and maximum sway of 40.5N and 7.9º respectively.

4.3.2 *When m_2 = 0.3Kg*

Figure 4.13, 4.14 and 4.15 shows the various controllers bang bang responses for the position, sway angle and control signal of the system when the payload mass m_2=0.3Kg.

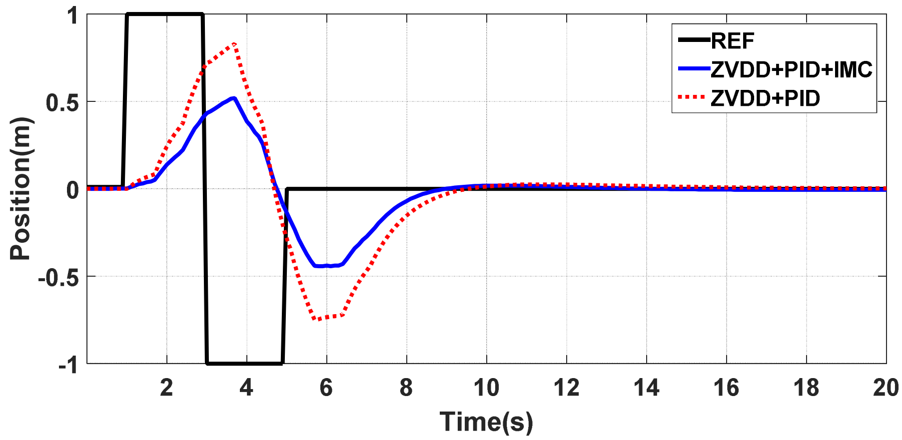


Figure 4.13 Position Bang-Bang response of the controller when m_2=0.3

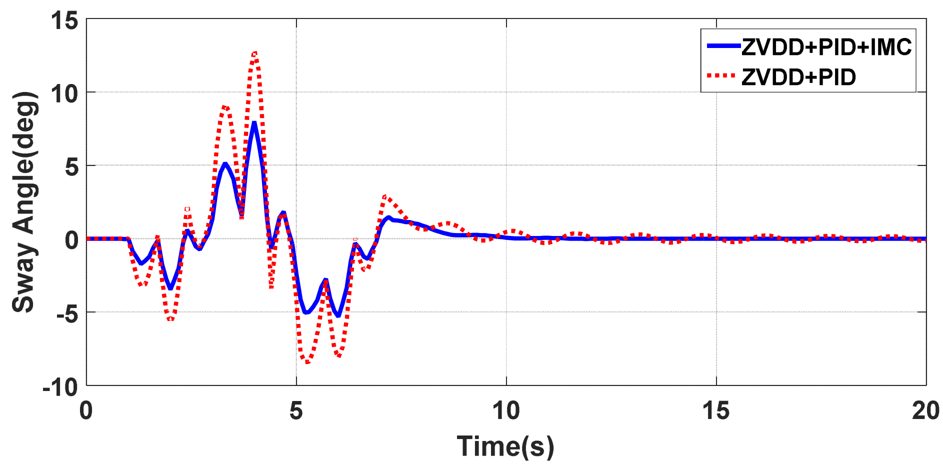


Figure 4.14 Sway Angle Bang Bang responses of the controller when m_2=0.3Kg

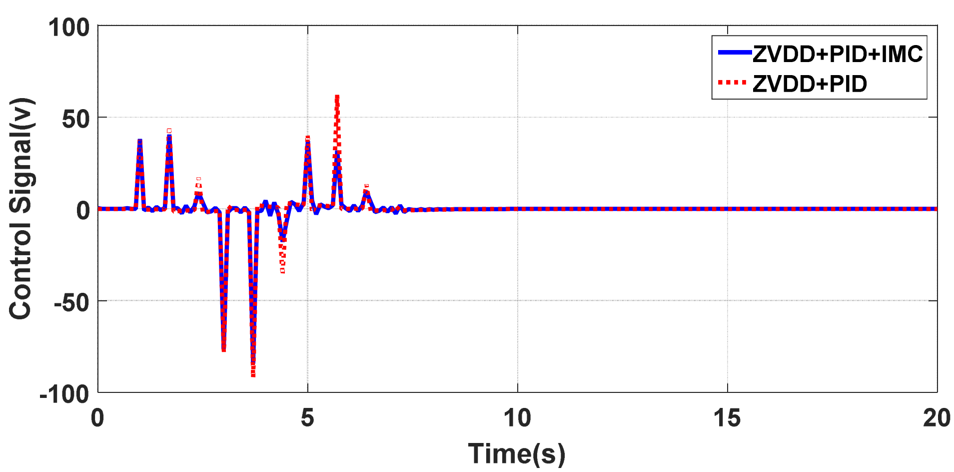


Figure 4.15 Control Signal Bang Bang responses of the controllers when m_2=0.3Kg

The summary of the above bang bang responses for the position, sway angle and control signal can be seen in Table 4.5.

Table 4.5 Summary of performance measures of GCS bang bang responses when m_2=0.3Kg

Controllers	**Maximum Control Signal (N)**	**Maximum Sway Reached (deg)**
ZVDD+PID	60	12.85
Proposed Controller	40	8

As can be seen from Table 4.5, the hybrid ZVDD and PID have both maximum control signal and maximum sway of 60N and 12.85º respectively while that of the hybrid ZVDD, PID and IMC controllers has both maximum control signal and maximum sway of 40N and 8º respectively.

4.3.3 *When m_2 = 0.1Kg*

Figure 4.16, 4.17 and 4.18 shows the various controllers bang bang responses for the position, sway angle and control signal of the system when the payload mass m_2=0.1Kg.

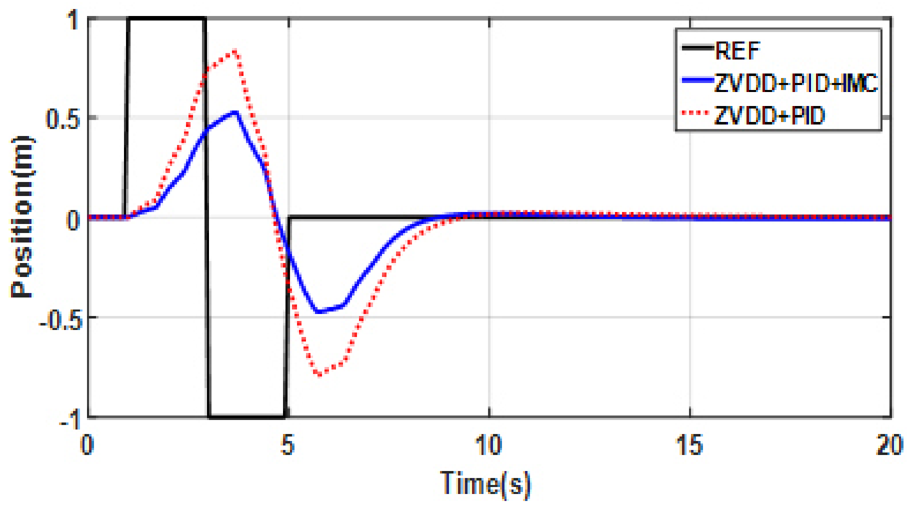


Figure 4.16 Position Bang Bang response of the controllers when m_2=0.1Kg

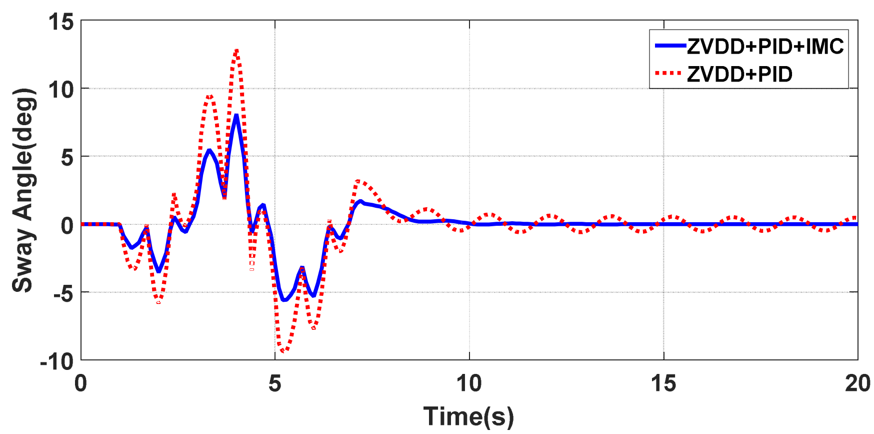


Figure 4.17 Sway Angle Bang bang responses of the controllers when m_2=0.1Kg

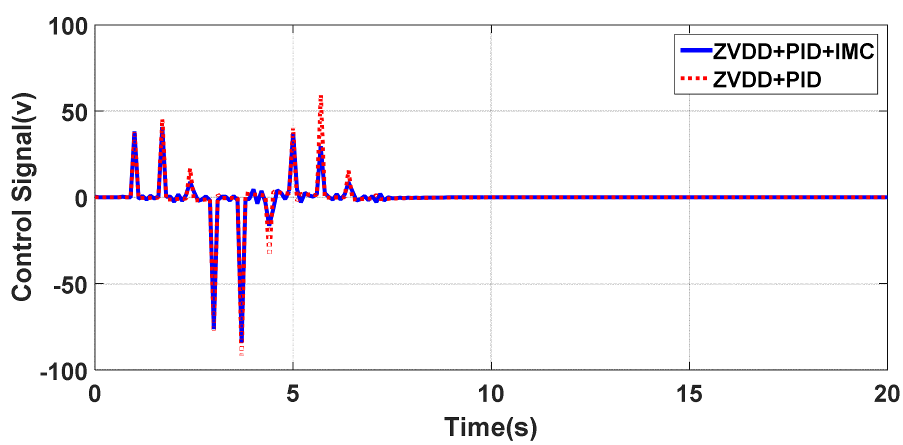


Figure 4.18 Control Signal Bang Bang responses of the controllers when m_2=0.1Kg

The summary of the above bang bang responses for the position, sway angle and control signal can be seen in Table 4.6

Table 4.6 Summary of performance measures of GCS bing bang responses when m2=0.1Kg

Controllers	Maximum Control Signal (N)	Maximum Sway Reached (deg)
ZVDD+PID	59.5	12.87
Proposed Controller	40	8

As can be seen from Table 4.4, hybrid ZVDD and PID have both maximum control signal and maximum sway of 59.5N and 12.87º respectively while that of the hybrid ZVDD, PID and IMC controllers have both maximum control signal and maximum sway of 40N and 8º respectively.

4.4 Discussion

As can be seen from table 4.1, 4.2 and 4.3 respectively when a step signal was set as input to the system, the hybrid ZVDD, PID and IMC controllers has no overshoot while that of the hybrid ZVDD and PID controllers has overshoot. The hybrid ZVDD, PID and IMC controllers achieved about 66%, 65% and 66% less sway respectively when compared to the hybrid ZVDD and PID controllers. Although the hybrid ZVDD and PID settles faster than the hybrid ZVDD, PID and IMC controllers but has a better control effort.

Similarly, as can be seen from Table 4.4, 4.5 and 4.6 respectively, when a bang bang signal was set as input to the system, the hybrid ZVDD, PID and IMC controllers achieved about 60% less sway than the hybrid ZVDD, and PID controllers. The hybrid ZVDD, PID and IMC controllers has a slower tracking ability when compared to the hybrid ZVDD and PID controllers. Control signal bang bang response for the hybrid ZVDD and PID controllers increase by 8% when compared with the hybrid ZVDD, PID and IMC controllers

4.5 Conclusion

This chapter discussed the simulation results of the position and sways angle control of 2D Gantry Crane System with hybrid ZVDD, PID and IMC controllers. The controlled system as examined under various test signals shows that better performance was achieved using the hybrid ZVDD, PID and IMC controllers because of its robustness to track different input signals to the system and also when subjected to different payload masses, the hybrid ZVDD, PID and IMC controllers performed better.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

The basic aim of this thesis is to control the position and sway angle of the 2d gantry crane by using the hybrid ZVDD, PID and IMC controllers. In order to realize this aim, a reasonable survey on position and sway angle control system of a 2D Gantry Crane System which gives rise to a literature review presented in chapter two. The mathematical model of the 2D Gantry Crane System was adopted as presented in chapter three. The hybrid ZVDD, PID and IMC controllers designed were set to provide precise tracking objective as well as controlling the sway angle of the system under various types of test signals, with the help of MATLAB/SIMULINK software, simulation results were obtained and presented accordingly.

5.2 Conclusion

In this thesis, the use of Hybrid ZVDD, PID and IMC controller in position and sway angle control of 2D Gantry Crane System reveals that enhance and effective way in control performance was achieved as compared to the hybrid ZVDD and PID controller. Simulation results obtained in this thesis shows that some of the limitations of the hybrid ZVDD and PID controllers were eliminated or drastically reduced with the use of the hybrid ZVDD, PID and IMC controllers. As can be seen from the result obtained in Table 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6, set point tracking was quite demonstrated under various test signals, better performance was found to be associated with the hybrid ZVDD, PID and IMC controllers as compared to its counterpart of hybrid ZVDD and PID interms of overshoot and sway angle reduction.

5.3 Contribution

1. The hybrid ZVDD, PID and IMC controllers when subjected to different payload masses of 0.5Kg, 0.3Kg and 0.1Kg gives better simulation results and performance as compared to hybrid ZVDD and PID. It achieved about 66% less sway compared to ZVDD and PID controller.
2. The control effort of Hybrid ZVDD, PID and IMC is lesser when compared to hybrid ZVDD and PID with about 7.3%

5.4 Recommendations

From the design, it can be seen that the precision of the system and the performance of the controller depends on the various values of the gains and accurate inverse transfer function of the non-linear system. For future work, it is recommended that there is 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. Utilization of the interactive tools will help in obtaining the accurate transfer functions of the models that are difficult to get ordinarily in nature and also help in designing the inverse model controller.

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