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STATE VARIABLE FEEDBACK CONTROL OF A GANTRY CRANE

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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NUR SYAZNI BINTI MUHAMAD NASRAH

ABSTRACT

The outcome of this project is to design a controller to meet the requirement of high positioning accuracy and small swing angle, motion and stabilization control of gantry crane. The dynamic of the gantry crane system has been modeled in state variable form to obtain state feedback gain matrix and system parameters has been defined and suitable desired poles has been specified to complete the dynamic modeling. The State Variable Feedback Control is chosen to be implemented in gantry crane control system because it can control multiple variables which are the gantry's position, speed, load angle and angular velocity at the same time. Block diagram constructed using Simulink which represents the controller has successfully achieved the objectives. An analytical analysis is conducted to study on the effect of system parameter changes. The scopes of studies involved will be on various types of gantry crane model, various control technique, gantry crane system modeling and simulation using MATLAB Simulink.

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INTRODUCTION

1.0 INTRODUCTION

1.1 Background of Study

There is an increasing need of effective automated means of lifting and transferring products especially in transportation field. In today's business world, importing and exporting products has been necessary in order to expand a company's market. So, the demand of quicker and safer handling of goods as well as accurate product positioning is crucial in the industry. An obvious need of highly effective gantry crane is for container lifting onto ships for exportation. Therefore, this project 'State Variable Feedback Control of a Gantry Crane' is supposed to model the dynamic gantry crane system in state space so that it controls multiple variables effectively in order to stabilize its motion to initiate smoother and quicker product transfer. This controller will help in increasing productivity and transportation quality.

1.2 Problem Statement

In order to move the gantry crane load of uncertain mass as quickly, accurately and safely as possible, state variable feedback is suitable to control the gantry's position, speed, load angle and angular velocity in order to achieve minimum error for stabilization control [1]. This state variable allows to model system with multiple inputs and multiple outputs simultaneously [2]. At the end of the project, the author should be able to prove that the state variable feedback controller can control gantry crane system effectively by complying with the requirement.

1.3 Significance of Study

The outcome of this project will benefit in less time consuming, higher productivity, safer work environment and efficient lifting and positioning job in the transportation and logistics as well as maintenance field. This study provides and adds another alternatives variation that can be utilised in the field of study so that greater improvements will be developed among researchers over time by comparing all available techniques nowadays. Further research and study in this area may initiate the development of standard dynamic controller for all gantry cranes to optimize its performance with varying load mass and environment. Analytical analysis on the system parameter changes will contribute in designing a reliable gantry crane controller complying with various job scopes in the industry.

1.4 Objectives and Scope of Study

The objectives of this project are as follows:

- To develop a mathematical model of the gantry crane system in state space.
- To design a control system for the gantry crane to meet the requirement of minimizing sway angle and accurate load positioning.
- To simulate the control system in Simulink using state-space block.
- To analyze on the effect of system parameter changes onto the system model.

The scopes of studies involved will be to study available control techniques for gantry crane and specifically the state variable feedback control technique in details. All variables associated with gantry crane system are to be specified and dynamic equations that describe the system will be created. Then, the dynamic system of gantry crane is modelled in state variable form. In order to design the control algorithm and implement it on the gantry crane system requires the author to familiarize with Simulink software. The author will also conduct study and research for any possibility of analyzing the effect of parameter changes onto the system.

CHAPTER 2
LITERATURE REVIEW/THEORY

2.0 LITERATURE REVIEW/ THEORY

2.1 Gantry Cranes

2.1.1 Introduction

Gantry Cranes are overhead structures with hoisting machines mounted on a frame or structure. The bridge for carrying the trolley or trolleys is rigidly supported on two or more legs running on fixed rails or other runway. Gantry cranes are for any type of cargo, such as timber, paper rolls, containers and any kind of bulk material [3]. Gantry cranes have become a widely accepted alternative to overhead bridge cranes. This type of crane is similar to the bridge crane except that it runs on a runway at the floor level [4]. Small non-powered gantry cranes are used in light duty applications such as small machine shops or automobile garages. These gantry cranes typically do not have a fixed path, but rather have rubber tires [5].

2.1.2 Basic Structure

The most basic gantry crane is an I girder with a truck hanging from the lower web, the truck would have a hook slung underneath and a 'chain block' might be suspended from this to lift the load. A chain block is a set of pulleys sometimes with interior gearing, operated by a long chain which hangs down in a loop. One end of the chain is fixed to either the upper or lower pulley and the load is suspended from a hook fitted on the trailing end. The I girder could be supported by legs at either end and in a building it could be suspended from the roof or walls [6].

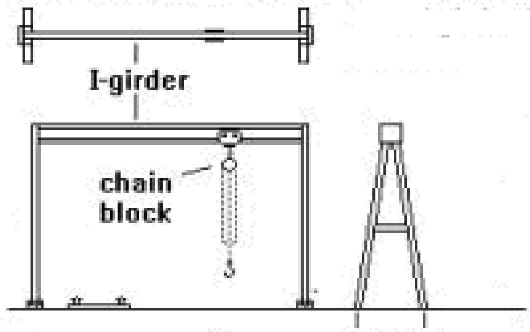


Figure 1 : Basic Structure of Gantry Crane [6]

2.1.3 Types of Gantry Cranes

2.2.3.1 Single-Leg Gantry

A combination of the bridge crane and gantry crane. One leg rides on the floor, while the other side's end truck rides on a runway beam [4].

2.2.3.2 Portainers

Portainer is a large dockside crane in the form of a specialized type of gantry crane used to load and unload container ships, and only seen at container terminals. Container cranes have a special lifting device called a spreader bar (also known as spreader or expandable spreader) for loading and discharging of containers. The whole crane runs on two rails so that it can traverse along the wharf (or the dock) to position the containers at any point on the length of the ship [7]. These machines are designed and manufactured to operate in the harshest of environmental conditions [8].

2.2.3.3 Workstation Gantry Cranes

Workstation Gantry Cranes can be mounted standing on the floor or from the ceiling [9]. Ceiling Mounted incorporating two parallel runways and a bridge suspended from the roof & providing full lifting coverage over a rectangular work area while Freestanding, is the same as Ceiling Mounted Gantry Cranes except that the runways are supported on a freestanding structure. Also, Monorail Cranes are a single rail supported either from the ceiling or a freestanding structure [10]. This type of crane is useful to move products along a single path. If something simply needs to be moved from one end of a factory to the other, a monorail is the ideal crane [11].

2.2.3.4 Rail Mounted Gantry Crane

A Rail Mounted Gantry Crane is typically used for movement of containers and loading of trucks. This crane type usually consists of three separate motions for transportation of material. The first motion is the hoist, which raises and lowers the material. The second is the trolley gear, which allows the hoist to be positioned directly above the material for placement. The third is the gantry, which allows the entire crane to be moved along the working area [12].

2.2 Available Control Techniques for Gantry Crane System

2.2.1 Controller with Operator Handling

Moving load from point to point is the most time-consuming task in the process and requires a skillful operator to accomplish it. Suitable methods to facilitate moving loads without inducing large sways are the focus of much current research. Crane automation can be divided into two approaches. In the first approach, the operator is kept in the loop and the dynamics of the loop are modified to make his job easier[13]. One way is to add damping by feeding back the load sway angle and its rate or by feeding back a delayed version of the sway angle[14].A second way is to avoid exciting the load near its natural frequency by adding a filter to remove this frequency from the input [15].This introduces a time delay between the operator action and the input to the crane. This delay may confuse the operator[13]. A third way is to add a mechanical absorber to the structure of the crane.[16]. Implementing this method requires a considerable amount of power[13].

2.2.2 Completely Automated Controller

In the second approach, the operator is removed from the loop and the operation is completely automated. This can be done using various techniques. The first is based on generating trajectories to transfer the load to its destination with minimum sway. These trajectories are obtained by input shaping or optimal control techniques. The resulting controller is open loop, which makes it sensitive to external disturbances and to parameter variations[13]. To avoid the open-loop disadvantages, many researchers[17,18] have investigated optimal control through feedback. Gupta and Bowal[19] developed a simplified open-loop anti-sway technique which works with low-end programmable logic controller (PLC) and adjustable speed drive (ASD).

A second technique is based on the feedback of the position and the sway angle. Feedback control is well-known to be less sensitive to disturbances and parameter variations. Hence, it is an attractive method for crane control design.[13] Ridout[20] developed a controller, which feeds back the trolley position and speed and the load swing angle. The feedback gains are calculated by trial and error based on the root-locus technique. Salminen[21] employed feedback control with adaptive gains while Benn,Burton, Ireland,Wang and Harley[1] employed state variable feedback control in state space, with feedback gains in both papers are calculated based on the pole-placement technique while Joshi and Rahn [22] developed a control law, based on Lyapunov theory to dampen the vibrations of the payload using the gantry motor, gantry position and velocity sensors, and a cable departure angle sensor. Design of the control gains is demonstrated using a root locus approach.

A third technique is based on dividing the controller design problem into two parts; an anti-sway controller and a tracking controller. Each one is designed separately and then combined to ensure the performance and stability of the overall. system[13]. The tracking controller can be a proportional-derivative (PD) controller [14] or a fuzzy logic controller (FLC) [23]. The anti-swing controller is designed by different methods such as Masoud et al. [14] who used a delayed feedback.

Raising the load during transfer is needed only to avoid obstacles. This motion is slow, and hence variations in the cable length can be considered as a disturbance to the system. The effect of the load weight on the dynamics is usually ignored[13]. However, Lee [24] and Omar and Nayfeh [25] consider it in the design of controllers for gantry and tower cranes, respectively. From these studies, they found out that for very heavy loads compared to the trolley weight, the system performance deteriorates if the load weight is not included in the controller design.

2.3 Modeling in State Space

The gantry crane system studied throughout this project is represented in state-space approach instead of transfer function form This is to essentially reduce the complexity of the mathematical expression in a modern complex system where outputs and inputs may be interrelated in a complicated manner. Modern control theory is based on the description of system equations in terms of *n* first-order differential equations which are combined into a first-order vector-matrix differential equation. The use of vector-matrix notation greatly simplifies the mathematical representation of systems of equations [26]. The state space representation is as follows:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \qquad (2.1)$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}u \qquad (2.2)$$

where **x =** state vector (*n*-vector)

u **=** control signal (scalar)

y = output vector (m-vector)

A = *n* x *n* constant matrix

B = *n* x 1 constant matrix

C = *m* x *n* constant matrix

D = *m* x 1 constant matrix

2.4 The Control System

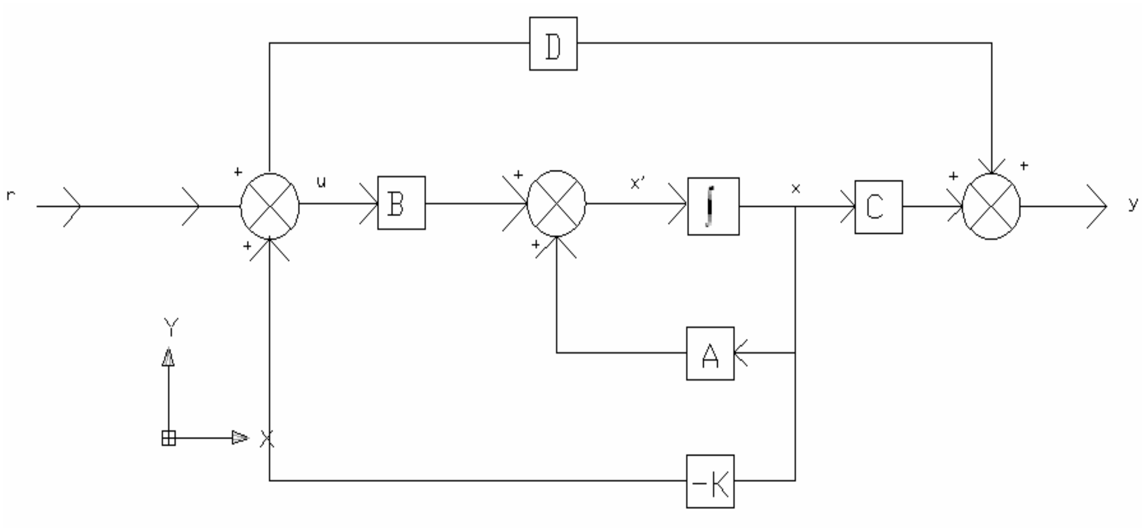


Figure 2 : State Variable Feedback Control System

In a typical feedback control system, the output, y, is fed back to the summing junction. For state-variable feedback system, instead of feeding back y, all the state variables will be fed back. For each state variable that is fed back to the control signal, u, through a gain k_i, there would be n gains, k_i, that could be adjusted to yield the required closed-loop pole values. The feedback through gains, k_i, is represented as in mathematical relation with control signal, u below and in Figure 2 by the feedback vector **K** [27].

$$u = r - \mathbf{Kx}$$

$$u = r - \begin{bmatrix} k_1 & k_2 & k_3 & k_4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

$$u = r - (k_1 x_1 + k_2 x_2 + k_3 x_3 + k_4 x_4) \qquad (2.3)$$

where the variables are as defined as Equations 2.1 and 2.2.

2.5 Pole-Placement Technique [26]

In pole-placement or pole-assignment design technique of control system in state space, all state variables are assumed measurable and are available for feedback. Poles of the closed loop system may be placed arbitrarily at any desired locations by means of state feedback provided the system considered is completely state controllable. Determination of the desired closed-loop poles based on the transient-response and/or frequency-response requirements, such as speed, damping ratio, or bandwidth, as well as steady state requirements. By determining appropriate desired poles, gain matrix for state feedback can be calculated to establish closed-loop system to achieve desirable value with minimum error.

2.6 Required State Feedback Gain Matrix K Determination

The method to determine required state feedback gain matrix K is as follows:

Step 1: The controllability condition for the system is checked to make sure it is completely state controllable.

Step 2 : From the characteristic polynomial for matrix **A**,

$$|s\mathbf{I} - \mathbf{A}| = s^n + a_1 s^{n-1} + \cdots\cdots + a_{n-1}s + a_n \quad (2.4)$$

the values $a_1, a_2, \ldots\ldots, a_n$ are determined.

Step 3: The transformation matrix **T** that transforms the system state equation into the controllable canonical form is determined. (If the given system equation is already in the controllable canonical form, then **T** = **I**). It is not necessary to write the state equation in the controllable canonical form. All needed here is to find the matrix **T**. The transformation matrix **T** is given by

$$\mathbf{T} = \mathbf{MW} \quad (2.5)$$

where **M** is the controllability matrix

$$\mathbf{M} = [\,\mathbf{B} \vdots \mathbf{AB} \vdots \cdots\cdots \vdots \mathbf{A}^{n-1}\mathbf{B}\,] \quad (2.6)$$

$$\mathbf{W} = \begin{bmatrix} a_{n-1} & a_{n-2} & \cdots & a_1 & 1 \\ a_{n-2} & a_{n-3} & \cdots & 1 & 0 \\ \bullet & \bullet & & \bullet & \bullet \\ \bullet & \bullet & & \bullet & \bullet \\ a_1 & 1 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \end{bmatrix} \quad (2.7)$$

Step 4: Using the desired eigenvalues which are represented as $\mu_1, \mu_2, \ldots, \mu_n$ (desired closed-loop poles), the desired characteristic polynomials is written as:

$$(s-\mu_1)(s-\mu_2) \cdots\cdots (s-\mu_n) = s^n + \alpha_1 s^{n-1} + \cdots\cdots + \alpha_{n-1}s + \alpha_n \quad (2.8)$$

and values of $\alpha_1, \alpha_2, \cdots\cdots, \alpha_n$ are determined.

Step 5: The required state feedback gain matrix K can be determined from [26]

$$\mathbf{K} = [\alpha_n - a_n \vdots \alpha_{n-1} - a_{n-1} \vdots \cdots\cdots \vdots \alpha_2 - a_2 \vdots \alpha_1 - a_1]\,\mathbf{T}^{-1} \quad (2.9)$$

2.7 Desired Response and Pole Stability

The output of the final simulation of under damped second order system is supposed to be as in example taken in other second order control system in Figure 3. The gantry crane system studied throughout this project is of fourth order system but characteristics of fourth and higher order system generally can be approximated as of the second order characteristics. So, transient requirement calculation and desired poles determination will be using the equations for the second order system. More oscillation will be expected from higher order system performance.

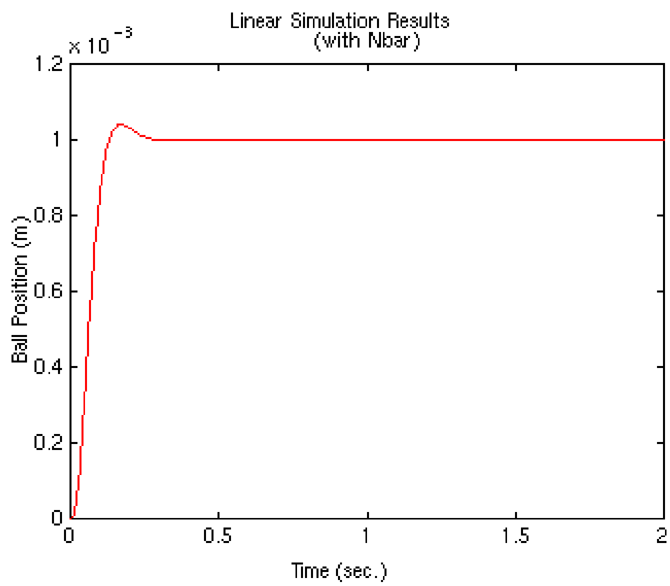


Figure 3 : Example of Second Order Response [28]

A real pole $pi = -\sigma$ in the left-half of the *s*-plane (refer Figure 4) defines an exponentially decaying component in the homogeneous response. The rate of the decay is determined by the pole location; poles far from the origin in the left-half plane correspond to components that decay rapidly, while poles near the origin correspond to slowly decaying components.

A complex conjugate pole pair $\sigma \pm j\omega$ in the left-half of the s-plane combine to generate a response component that is a decaying sinusoid. The rate of decay is specified by location of poles [29].

Thus, desired closed-loop poles are determined based on these requirements; to place those poles on left-half of the s-plane. Pole is also chosen so that the system exhibit under damped system so that it is not too oscillatory and not too damped (totally static) for such condition is impossible in real system.

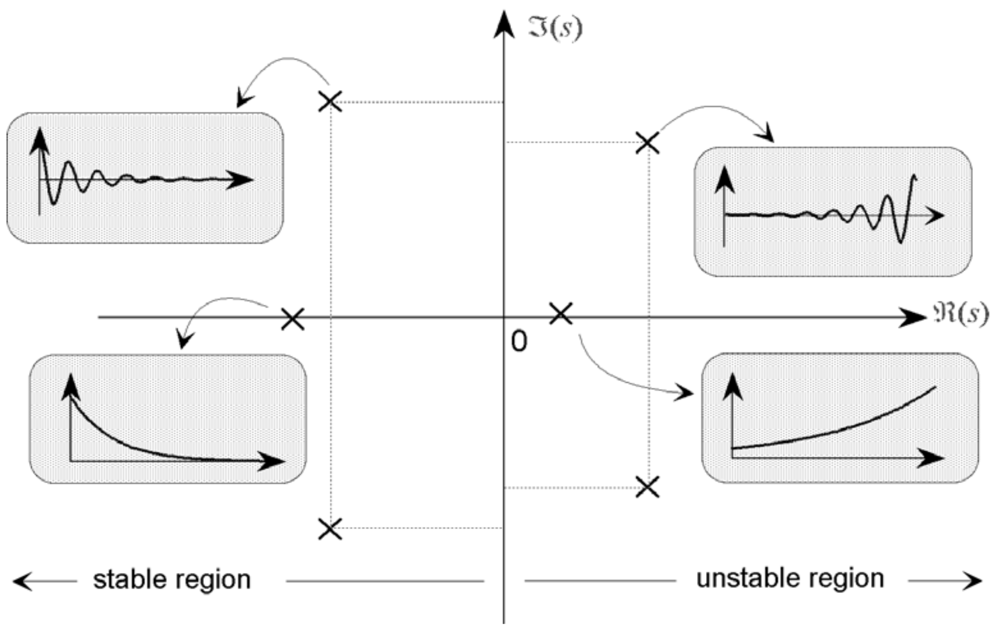


Figure 4 : Response From The System Pole Locations On The Pole-Zero Plot

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.0 METHODOLOGY

3.1 Gantt Chart

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	-Block Diagram Modification -Project objective finalization -Compare output with industry requirement -System variables adjustment	■	■	■	■	■	■	■	■			MID-SEMESTER BREAK		EXAMINATION WEEKS					
2	Submission of Progress Report I				●														
3	Submission of Progress Report II								●										
4	Analytical analysis on parameters changes effect on system -Block diagram design for changing parameter input									■	■		■						
5	Poster Exposition												●						
6	Submission of Dissertation Draft																●		
7	Oral Presentation																	●	
8	Submission of Hardbound Dissertation																		●

● Suggested milestone

■ Process

Figure 5 : Gantt Chart for FYP II Semester July 2008

3.2 Flow Chart

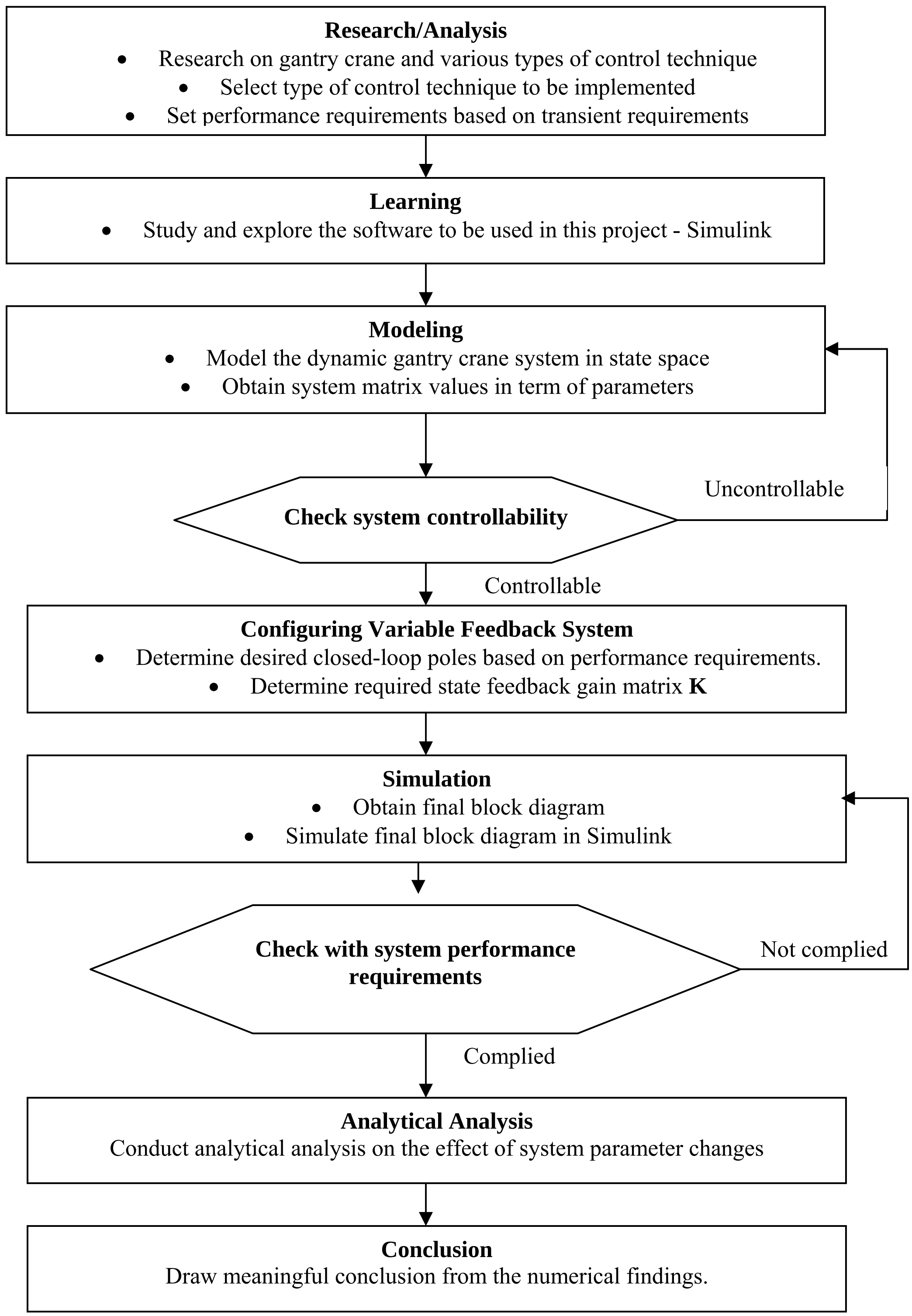
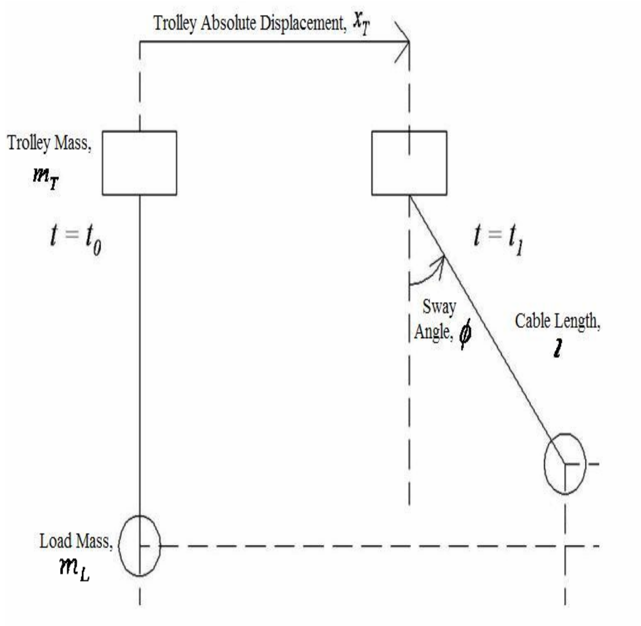


Figure 6 : Project Flow Chart

3.3 The Dynamic Gantry Crane System Modelling In State Variable Form

3.3.1 Equations of Motion Derivation



Nomenclatures for Figure 7 and Figure 8

m_T : mass of the trolley
m_L : mass of the pendulum
x_T : absolute displacement of the trolley in x-axis
x_S, z_S : absolute displacement of the pendulum along x and z axes
x_{ST} : displacement of the pendulum relative to the trolley along the x-axis
l : cable length
ϕ : pendulum displacement angle
u : control force applied to trolley
g : gravity acceleration
b: coefficient of friction
N and P : reaction forces at pendulum pin

Figure 7 : The pendulum on the left are at their initial rest position. The one on the right determines desired closed-loop poles based on performance requirements [30].

Figure 7 defines the parameter by showing the pendulum and trolley at two different positions representing the basic two dimensional gantry crane system. The entire project will be based on the figure shown. The trolley is moving horizontally and the pendulum cable is assumed to be rigid. It is assumed also that the pendulum mass is concentrated at the lower tip of the cable and the cable is assumed to be massless. It is desired to keep the pendulum in a vertical position from the moment the crane is moved by applying force onto it and all the way upon reaching the expected position. The slanted pendulum can be brought back to the vertical position when appropriate control force u is applied to the trolley. At the end of each process, it is desired to bring the trolley to a desired final position, x_T. The controller will be designed using the state feedback control method by the pole placement technique. The first method is used in modelling this dynamic gantry crane system in state variable form [26].

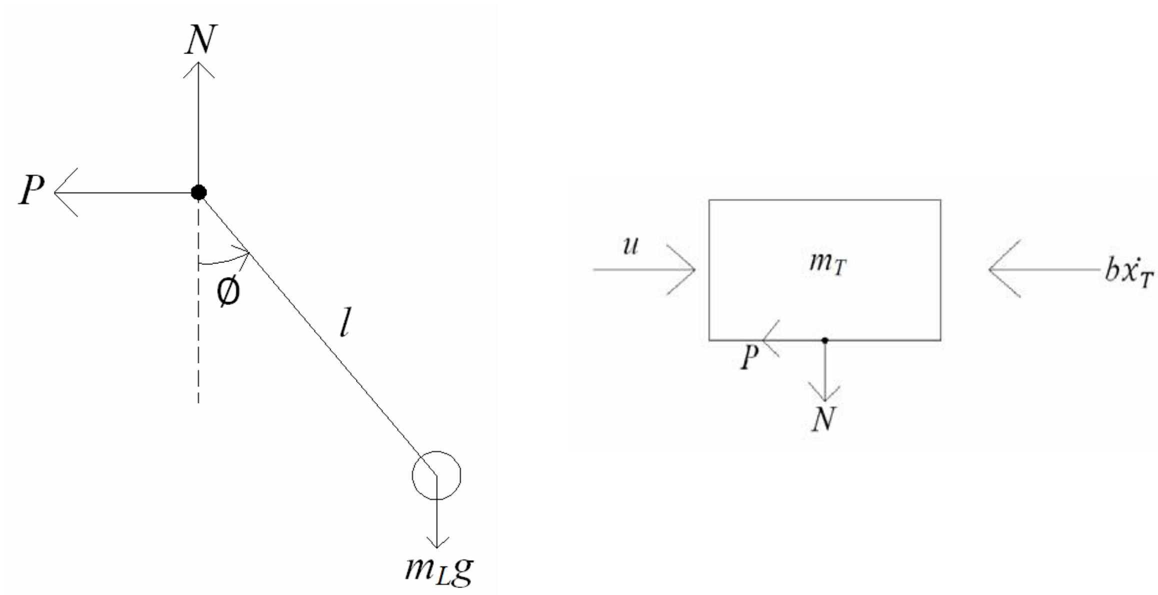


Figure 8 : Free-body diagram of the simple pendulum system [26]

The free body diagram shown in Figure 8 is considered to derive the equations of motion for the system. The rotational motion of the pendulum cable about its center of gravity can be described by

$$I\ddot{\emptyset} = Nl\sin\emptyset + Pl\cos\emptyset \tag{3.1}$$

where *I* is the moment of inertia of the cable about its center of gravity. The horizontal motion of center of gravity of pendulum cable is given by

$$m_L \frac{d^2}{dt^2}(x_T + l\sin\phi) = P \tag{3.2}$$

The vertical motion of center of gravity of pendulum cable is

$$m_L \frac{d^2}{dt^2}(l - l\cos\phi) = N - m_L g \tag{3.3}$$

The horizontal motion of the trolley is described by

$$m_T \frac{d^2 x_T}{dt^2} + b\frac{d}{dt}x_T + P = u \tag{3.4}$$

Because equations (3.1) through (3.4) involve sin ϕ and cos ϕ, they are nonlinear equations. If we assume angle ϕ to be small, so sin $\phi \approx \phi$ and cos $\phi \approx 1$. Then, those equations may be linearized as follows:

$$I\ddot{\phi} = Nl\phi - Pl \tag{3.5}$$

$$m_L\ddot{x}_T + m_L l\ddot{\phi} = P \tag{3.6}$$

$$0 = N - m_L g \tag{3.7}$$

$$m_T\ddot{x}_T + b\dot{x}_T + P = u \tag{3.8}$$

Combining Equation (3.6) and (3.8) obtains

$$(m_T + m_L)\ddot{x}_T + b\dot{x}_T + m_L l\ddot{\phi} = u \tag{3.9}$$

while Equation (3.10) is obtained from combining Equation (3.5), (3.6) and (3.7)

$$(I + m_L l^2)\ddot{\phi} + m_L l\ddot{x}_T = m_L gl\phi \tag{3.10}$$

Equation (3.9) and (3.10) are the equations of motion describing the dynamics of the system where I is the moment of inertia of the pendulum about its center of gravity. Since in this system the pendulum mass is concentrated at the lower tip of the cable, the center of gravity is the center of the pendulum ball. In this analysis, the moment of inertia of the pendulum ball about its center of gravity is zero, or I=0. Then, the above equations of motion becomes as follows:

$$(m_T + m_L)\ddot{x}_T + b\dot{x}_T + m_L l\ddot{\phi} = u$$

$$m_L l^2\ddot{\phi} + m_L l\ddot{x}_T = m_L gl\phi \tag{3.11}$$

Then, derivating $\ddot{\phi}$ from Equation 3.9 and insert it into Equation 3.11 will obtain Equation 3.12:

$$\ddot{x}_T = -\frac{b}{m_T}\dot{x}_T - \frac{m_L g}{m_T}\phi + \frac{1}{m_T}u \tag{3.12}$$

While derivating $\ddot{x}$ from Equation 3.9 and insert it into Equation 3.11 will obtain Equation 3.13:

$$\ddot{\phi} = \frac{b}{m_T l}\dot{x}_T + \frac{(m_T + m_L)g}{m_T l}\phi - \frac{1}{m_T l}u \tag{3.13}$$

3.3.2 The State-Space Representation

State variables for this system are defined as

$$x_1 = x_T \tag{3.14}$$

$$x_2 = x'_T \tag{3.15}$$

$$x_3 = \emptyset \tag{3.16}$$

$$x_4 = \dot{\emptyset} \tag{3.17}$$

The outputs of the system are considered as ϕ and x, or

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} x_T \\ \phi \end{bmatrix} \tag{3.18}$$

Then, from the definition of state variables and Equation (3.12) and Equation (3.13), equations as stated below are obtained:

$$x'_1 = \frac{d}{dt} x_T = x_2 \tag{3.19}$$

$$x'_2 = \frac{d}{dt} x'_T = \ddot{x}_T = -\frac{b}{m_T}\dot{x}_T - \frac{m_L g}{m_T}\emptyset + \frac{1}{m_T}u \tag{3.20}$$

$$x'_3 = \frac{d}{dt}\emptyset = x_4 \tag{3.21}$$

$$\dot{x}_4 = \frac{d}{dt}\dot{\phi} = \ddot{\phi} = \frac{b}{m_T l}\dot{x}_T + \frac{(m_T + m_L)g}{m_T l}\phi - \frac{1}{m_T l}u \tag{3.22}$$

In terms of vector-matrix equations:

$$\frac{d}{dt}\begin{bmatrix} x_T \\ \dot{x}_T \\ \phi \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{b}{m_T} & -\frac{m_L g}{m_T} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{b}{m_T l} & \frac{(m_T + m_L)g}{m_T l} & 0 \end{bmatrix} \begin{bmatrix} x_T \\ \dot{x}_T \\ \phi \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m_T} \\ 0 \\ -\frac{1}{m_T l} \end{bmatrix} u \tag{3.23}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_T \\ \dot{x}_T \\ \phi \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u \tag{3.24}$$

Equations (3.23) and (3.24) give a state-space representation of the pendulum system and can be rewritten as:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}u$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{b}{m_T} & -\dfrac{m_L g}{m_T} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{b}{m_T l} & \dfrac{(m_T + m_L)g}{m_T l} & 0 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 \\ \dfrac{1}{m_T} \\ 0 \\ -\dfrac{1}{m_T l} \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad \mathbf{D} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

3.3.3 System Parameters

For this base system model construction, the following parameters for this gantry crane are identified from specification of overhead crane use in UTP laboratory since gantry crane and overhead crane possess the same characteristics [31]:

- Mass of the trolley, m_T = 110 kg
  = **0.11 tonnes**
- Mass of the pendulum, m_L = **1 tonnes**
- Pendulum length, l = **6.5 m** (constant)
- Maximum span, x_T = **5.42 m**
- Gravity acceleration, g = **9.81m/s2**
- Coefficient of Friction,b (steel-steel) = **0.57** [32]

Which are plugged in the **A**, **B**, **C** and **D** matrices to obtain:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -5.18 & -89.18 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0.8 & 15.23 & 0 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 \\ 9.09 \\ 0 \\ -1.4 \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad \mathbf{D} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

3.3.4 System Controllability Check

To check if the system is completely state controllable, command 'rank **M' in MATLAB** should equal to n which is 4 for this system where

$$\mathbf{M} = [\mathbf{B} \vdots \mathbf{AB} \vdots \mathbf{A}^2\mathbf{B} \vdots \mathbf{A}^3\mathbf{B}] = \begin{bmatrix} 0 & 9.1 & -47.1 & 368.8 \\ 9.1 & -47.1 & 368.8 & -2557.5 \\ 0 & -1.4 & 7.2 & -58.9 \\ -1.4 & 7.2 & -58.9 & 404.4 \end{bmatrix}$$

Using Matlab, rank (**M)** =n =4

Thus, the system is completely state controllable and arbitrary pole-placement is possible.

3.3.5 Transfer Function Representation

The state space representation of the system above is converted into transfer function representation. This is to check for the open-loop poles of the system to determine its stability. Refer to Appendix A for MATLAB programme used to convert the representation.

Transfer Function 1, (ϕ system)

$$= \frac{5.42s^4 + 28.09s^3 - 73.45s^2 - 42.39s - 13.72}{s^4 - 5.182s^3 - 15.23s^2 - 7.821s}$$

$$= \frac{5.42(s+6.972)(s-2.319)(s^2+0.5287s+0.1566)}{s(s+7.157)(s-2.426)(s+0.4505)} \quad (3.25)$$

Transfer Function 2, (x_T system)

$$= \frac{-1.399s + 1.601\times10^{-15}}{s^3 + 5.182s^2 - 15.23s - 7.821}$$

$$= \frac{-1.3986s}{(s+7.157)(s-2.426)(s+0.4505)} \quad (3.26)$$

3.3.6 Open-Loop System Stability Check

From the transfer function shown above, the poles of the open-loop system which are the eigenvalues of the matrix **A** are 0, -7.157, -0.4505 and 2.426. One pole on the system positive real axis shows that the system is open-loop unstable. So, the state variable of the system have to be fed back to achieve stability [26].

3.3.7 Desired Closed-Loop Poles Determination

From transient requirement which is 10% overshoot, %OS which is a general acceptable percentage overshoot, desired closed-loop poles are calculated using these equations:

$$\text{Damping factor}, \xi = \frac{(-\log(\%OS/100))}{\sqrt{\pi^2 + \log(\%OS/100)^2}}$$

$$= \frac{(-\log(10/100))}{\sqrt{\pi^2 + \log(10/100)^2}} = 0.59$$

which represents under damped system.

$$\text{Natural frequency}, \omega_n = \sqrt{\frac{g}{l}} = \sqrt{\frac{9.81m/s^2}{6.5m}} = 1.23 rad/s$$

$\therefore$ Desired dominant closed-loop poles are calculated as:

$$\text{Desired poles}, \mu_1, \mu_2 = -\xi\omega_n \pm \omega_n\sqrt{1-\xi^2} = -0.73 \pm 0.99j$$

while the remaining two closed-loop poles, $\mu_3 = -1.46$ and $\mu_4 = -2.46$ are located far to the left of the dominant pair of closed-loop poles and therefore, the effect on the response of μ_3 and μ_4 is small. So, the damping requirements will be satisfied [26].

Such transient requirements are determined arbitrarily from usual control design application from reference to gain most basic control design.

3.3.8 State-Feedback Gain Matrix K Determination

Desired poles obtained from the transient requirement are then used to calculate gains needed to feed back system state variables to make the system stable and achieve desired output values. Refer Appendix B for MATLAB programme used to determine system gain matrix, K. The closed-loop system gains are:

K = [-0.0723 -0.8491 -14.8863 -4.2148]

Command 'place(A,B,P)' used to calculate gain vector **K** such that the state feedback places the closed-loop poles at the locations P.

3.4 Block Diagram Acquisition

Several trials and options are run to determine the correct block diagram and simulation program to design a reliable controller.

3.4.1 Open Loop System Response

In open loop system, input is fed into the controller to evaluate the resulting output. Step input is chosen as input for convenience in evaluating system response because of the drastic changes in the step input. The open loop system response is obtained to be compared with the closed-loop system response. The **A, B, C** and **D** matrices determined in part **3.3.3** are incorporated into the matrices block in the block diagram

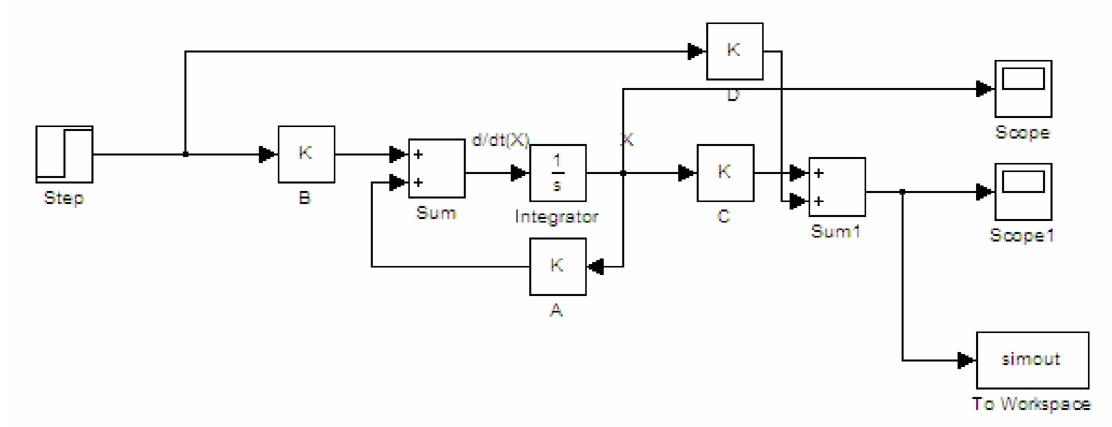


Figure 9 : Block Diagram for Open Loop System in State Space

The response for the open-loop system is such as follows:

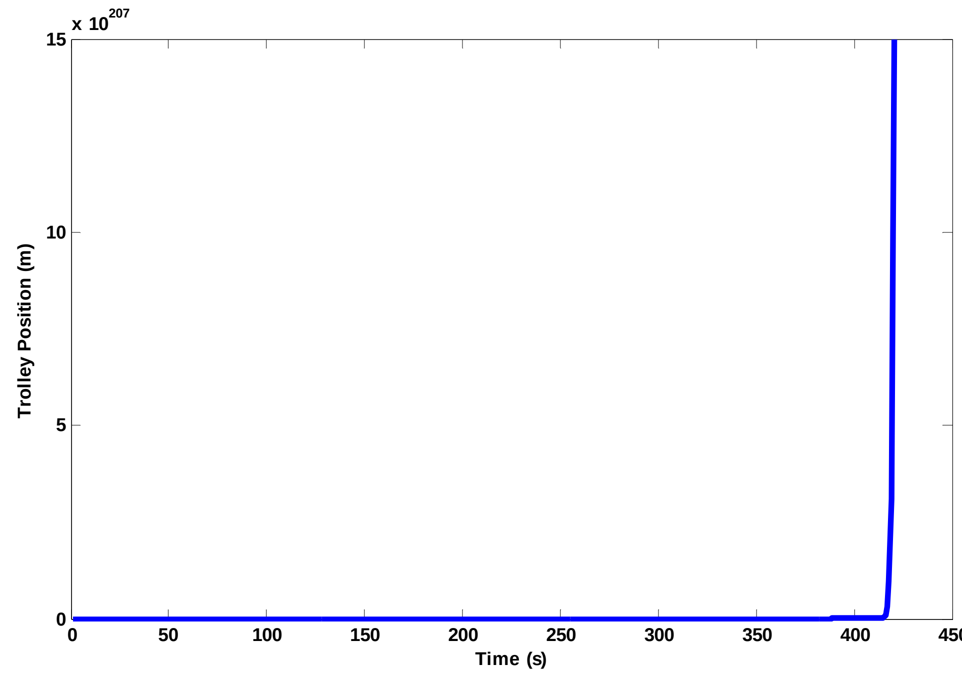


Figure 10 : Response for Trolley Position, x_T in Open Loop System in State Space

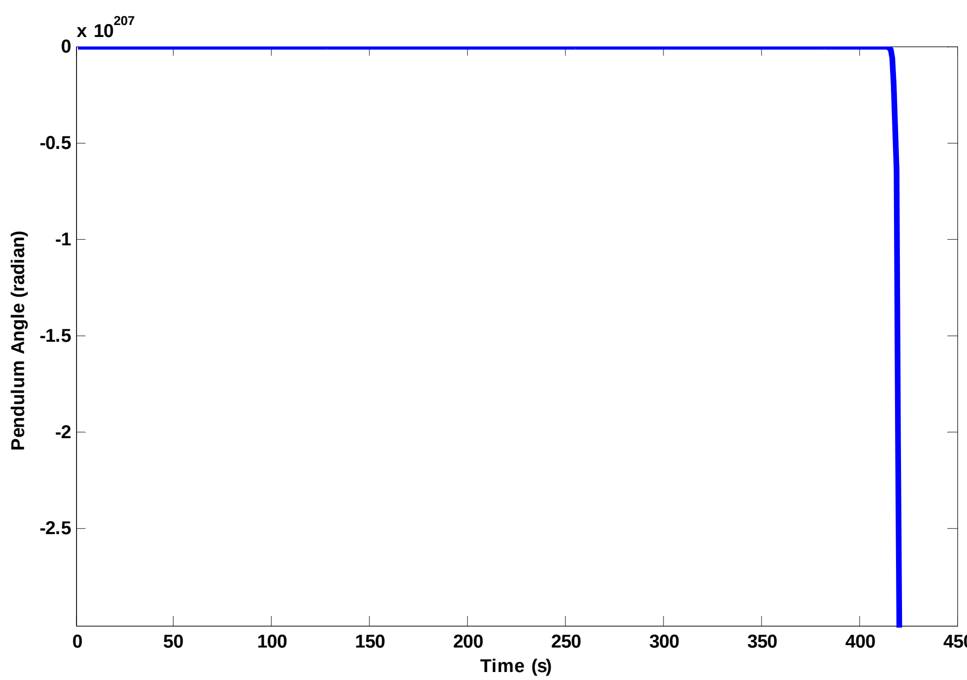


Figure 11 : Response for Sway Angle, ϕ in Open Loop System in State Space

3.4.2 Closed-Loop System Response

For closed-loop system analysis, first, block diagrams with gains,k_i calculated via pole-placement method are run to observe if it can achieve the system requirement. Then, a closed-loop system with integral action is constructed to eliminate the system steady-state error so that desired output can be achieved.

3.4.2.1 Closed-Loop System with Feedback Gains

The presence of feedback gain affects the A matrix since the new closed-loop system **A** matrix should incorporate the feedback gains. The new **A** matrix is as follows:[26]

$$\dot{\mathbf{x}}=\mathbf{Ax}+\mathbf{Bu}$$

where $u = -\mathbf{Kx}$,

$$\dot{\mathbf{x}}=(\mathbf{A}\text{-}\mathbf{BK})\mathbf{x}$$

$$\mathbf{A}_{new}=\mathbf{A}\text{-}\mathbf{BK} \tag{3.27}$$

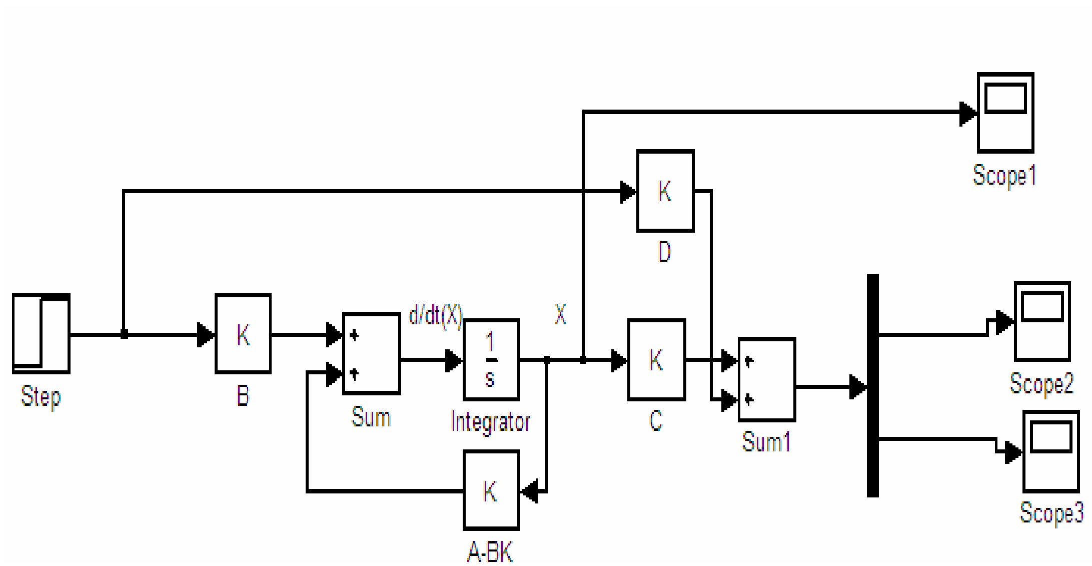


Figure 12 : Block Diagram for Closed-Loop System in State Space

The response for the closed-loop system with feedback gains is such as follows:

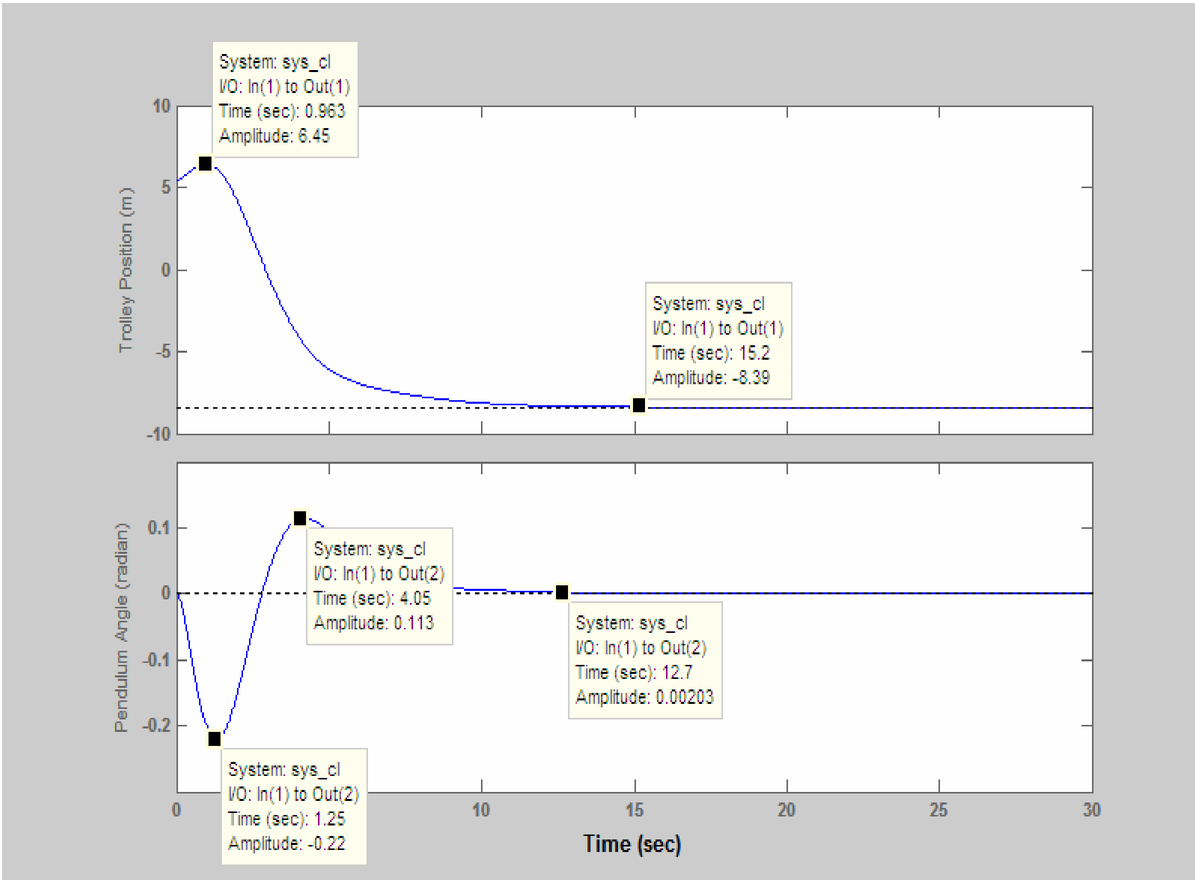


Figure 13 : Response for Closed-Loop System in State Space

3.4.2.2 Closed-Loop System with Feedback Gains and Integral Action[33]

Integral action incorporated in this controller functions to reduce the steady-state error since previous controller cannot achieve the desired output values. The presence of integral gain to reduce error changes system matrices structure as follows:

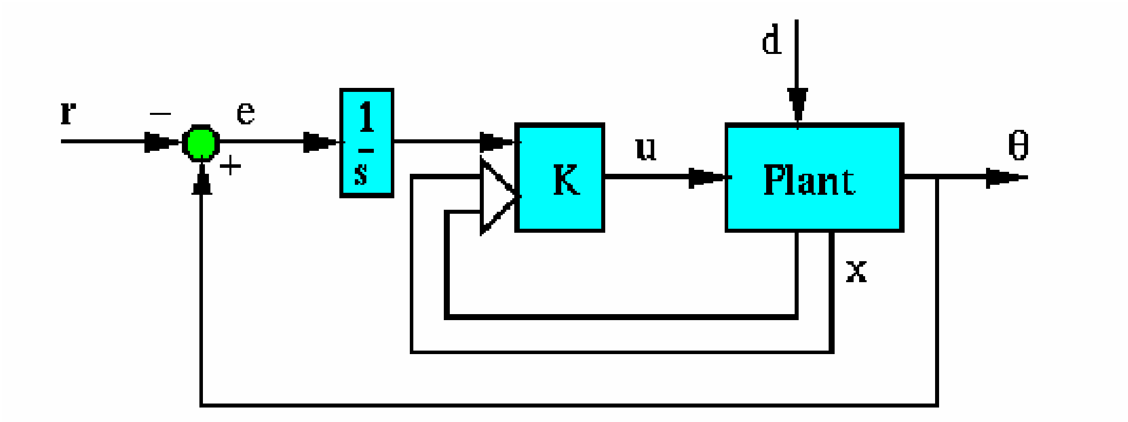


Figure 14 : Closed-Loop System with Integral Action

The integrator is modelled by augmenting the state equations with an extra state which is the integral of the output. This adds an extra equation which states that the derivative of the integral of theta is theta. This equation will be placed at the top of the matrices. The input, r, now enters the system before the integrator, so it appears in the newly added top equation. The output of the system remains the same.

$$\frac{d}{dt}\begin{bmatrix}\int x\\ x\\ \dot{x}\\ \phi\\ \dot{\phi}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & -5.18 & -89.18 & 0\\ 0 & 0 & 0 & 0 & 1\\ 0 & 0 & 0.8 & 15.23 & 0\end{bmatrix}\begin{bmatrix}\int x\\ x\\ \dot{x}\\ \phi\\ \dot{\phi}\end{bmatrix}+\begin{bmatrix}-5.42\\ 0\\ 0\\ 0\\ 0\end{bmatrix}r \tag{3.28}$$

$$y=\begin{bmatrix}0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\int x\\ x\\ \dot{x}\\ \phi\\ \dot{\phi}\end{bmatrix} \tag{3.29}$$

$$B_{au}=\begin{bmatrix}0\\ 0\\ 9.09\\ 0\\ -1.4\end{bmatrix} \tag{3.30}$$

Equations 3.28 and 3.29 represent the dynamics of the system before the loop is closed. The matrices in this equation are referred to as $\mathbf{A}_a$, $\mathbf{B}_a$, $\mathbf{C}_a$, and $\mathbf{D}_a$. The state vector of the augmented system as is referred as $\mathbf{x}_a$. Note that the reference, r, does not affect the states (except the integrator state) or the output of the plant since there is no path from the reference to the plant input, u, without implementing the feedback matrix, $\mathbf{K}_c$.

In order to find the closed loop equations, we have to look at how the input, u, affects the plant. In this case, it is exactly the same as in the unaugmented equations. Therefore, there is a vector, $\mathbf{B}_{au}$ (Equation 3.30) which replaces $\mathbf{B}_a$ when u is treated as the input. This is just the old **B** vector with an extra zero added as the first row. Since u=$\mathbf{K}_c$*$\mathbf{x}_a$ is the input to the plant for the closed loop, but r is the input to the closed loop system, the closed loop equations will depend on both $\mathbf{B}_{au}$ and $\mathbf{B}_a$.

The closed loop equations will become:

$$\dot{\mathbf{x}}_a = [\mathbf{A}_a + \mathbf{B}_{au}\mathbf{K}]\mathbf{x}_a + \mathbf{B}a\, r \qquad (3.31)$$

$$\mathbf{y} = \mathbf{C}_a\mathbf{x}_a \qquad (3.32)$$

Now, the integral of the output will be fed back, and will be used by the controller to remove steady state error, another pole will be placed at -10, which will be faster than the rest of the poles. $\mathbf{B}_{au}$ will be used in the 'place' command instead of $\mathbf{B}_a$ Since the closed-loop system matrix depends on $\mathbf{B}_{au}$. Refer to Appendix C for the full MATLAB programme for the closed-loop system with integral action.

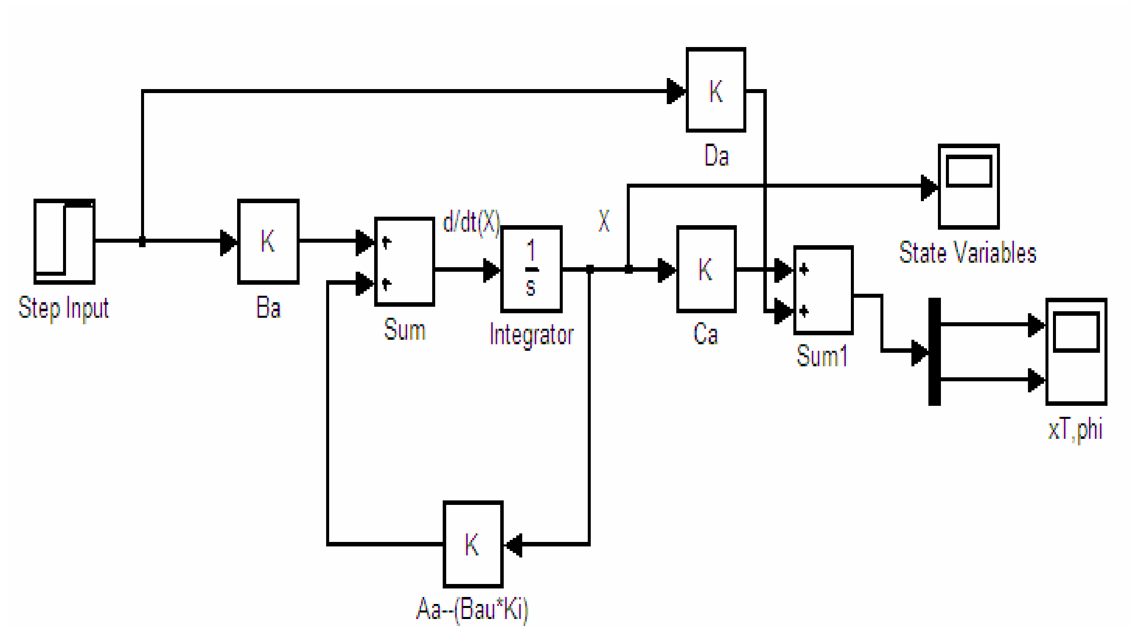


Figure 15: Block Diagram for Closed Loop System with Integral Action

The response for the closed-loop system with feedback gains and integral action is such as follows:

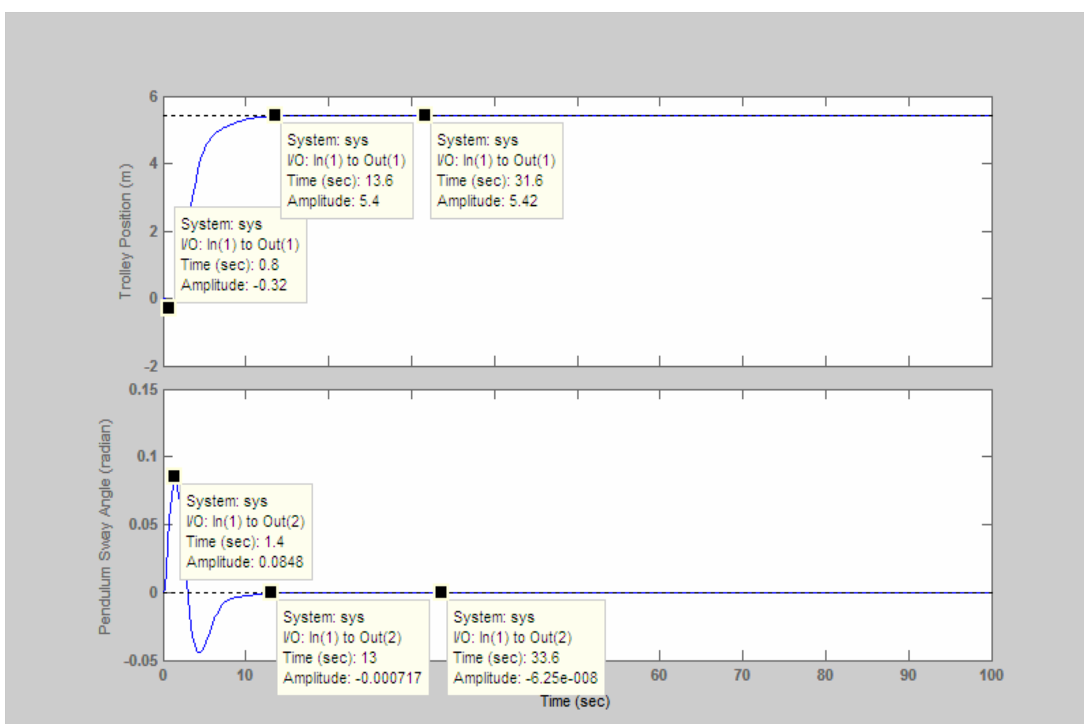


Figure 16 : Response for Closed-Loop System with Integral Action

3.5 Analysis of the Effect of Varying System Parameters

System controllability is checked each time the system parameter is change. The controllability check shows that the system of each analysis on the varying system parameter below is controllable and pole-placement method is permitted.

3.5.1 The Effect of Varying Pendulum Cable Length

The maximum length of the cable for the crane used for this study is 6.5 metres. The analysis will determine the effect of using shortest possible cable and also longer cable than specified.

The output when pendulum cable length,*l* used is 1 m is as follows:

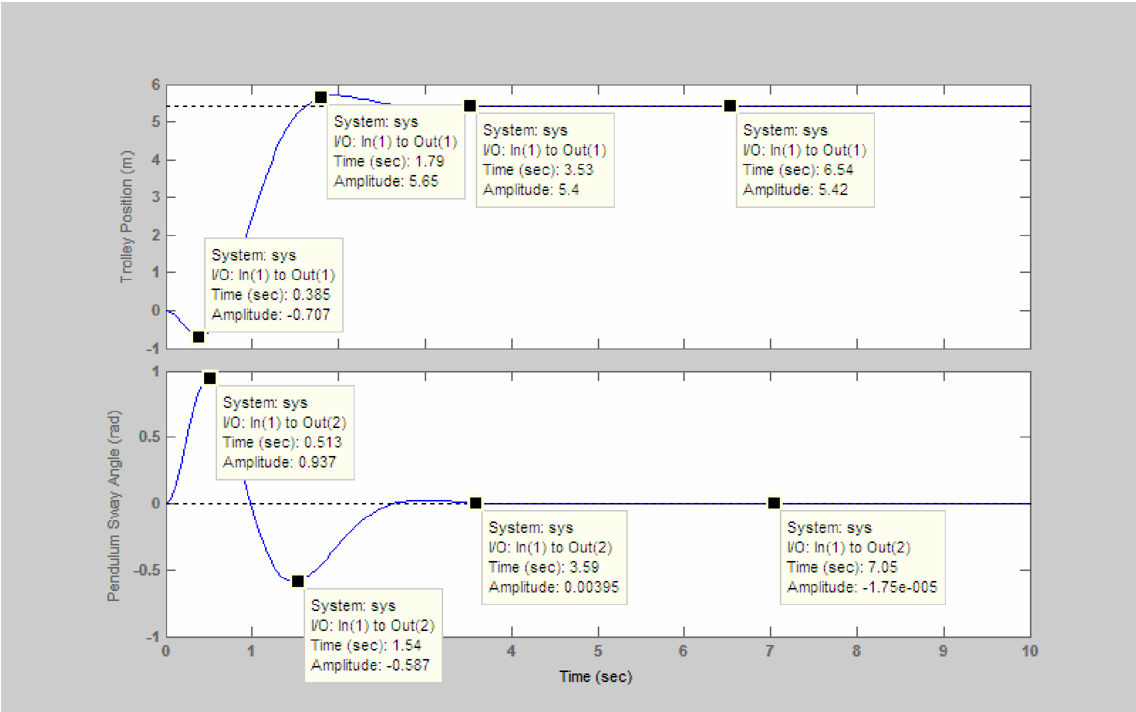


Figure 17 : Response for Controller with *l*=1m

The output when pendulum cable length,*l* used is 4 m is as follows:

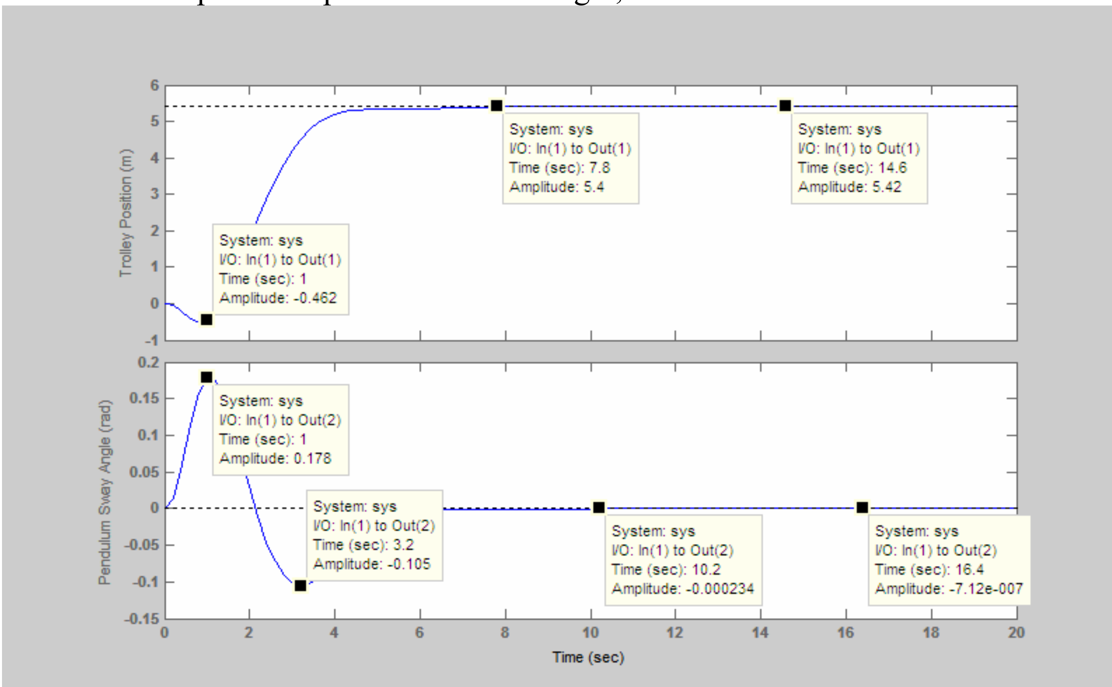


Figure 18 : Response for Controller with *l*=4m

The output when pendulum cable length,*l* used is 8 m is as follows:

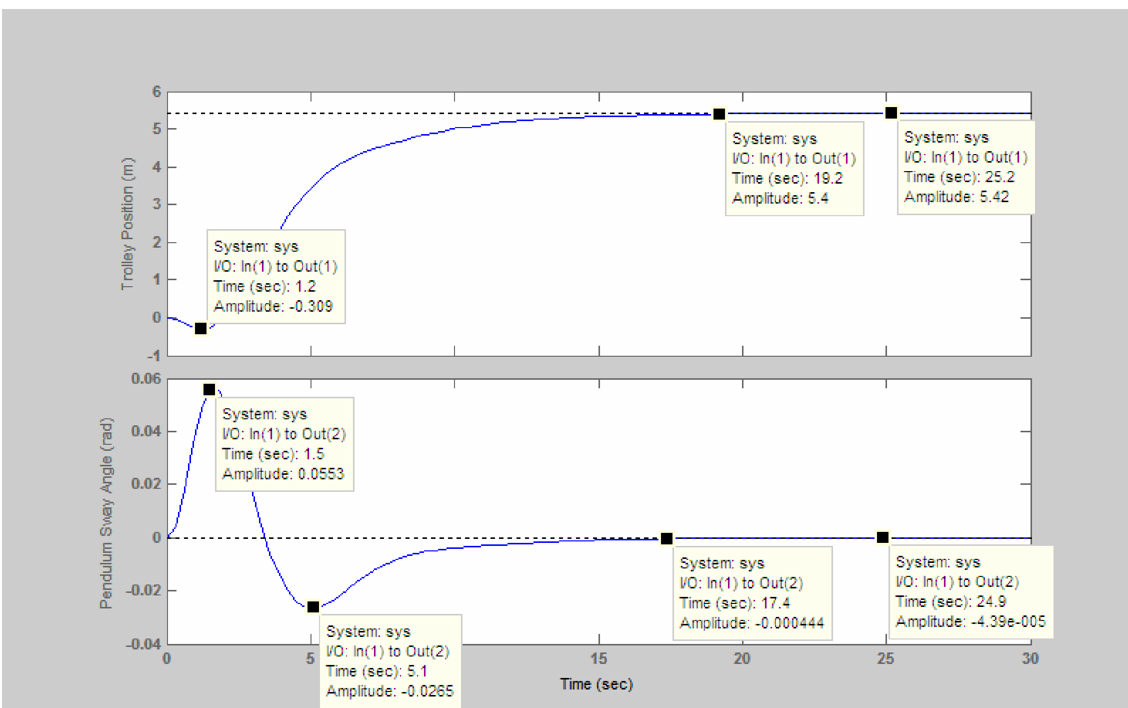


Figure 19 : Response for Controller with *l*=8m

3.5.2 The Effect of Varying Load Mass

The maximum load specified for the reference crane system is 1 tonne. An analysis will be conducted to determine the effect of varying the load mass to smaller than 1 tonnes till maximum possible mass the system can attain.

The output when pendulum load mass, m_L used is 0.05 t is as follows:

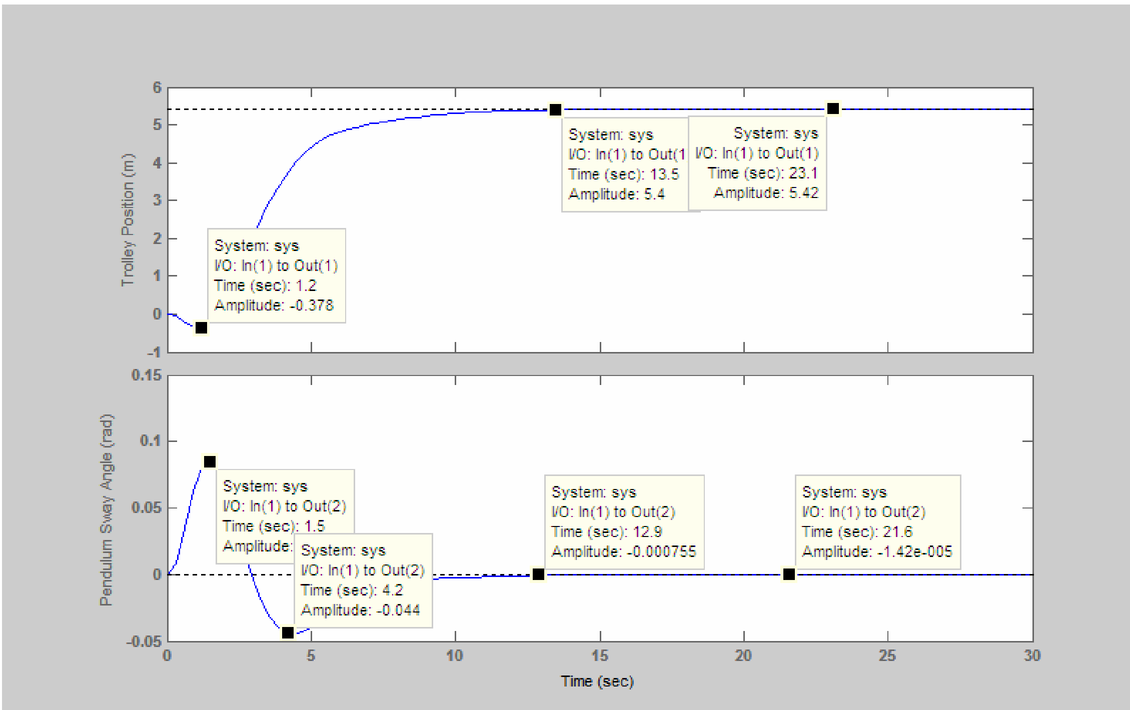


Figure 20 : Response for Controller with m_L=0.05t

The output when pendulum load mass, m_L used is 5 t is as follows:

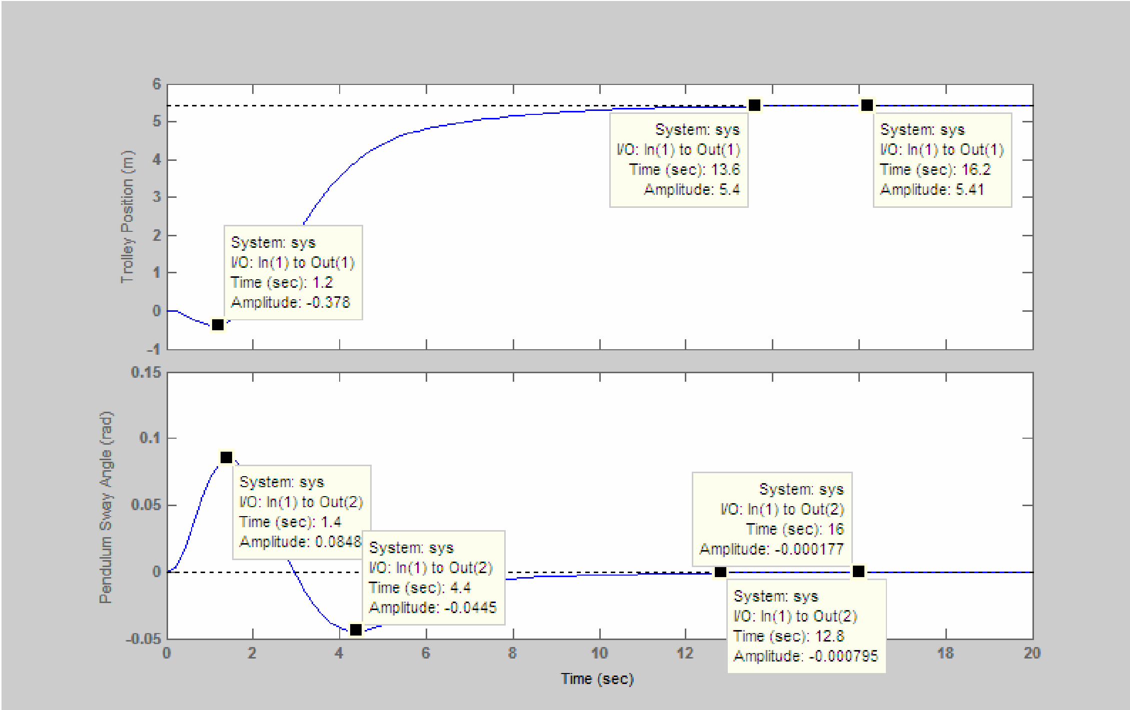


Figure 21 : Response for Controller with m_L=5t

The output when pendulum load mass, m_L used is 50 t is as follows:

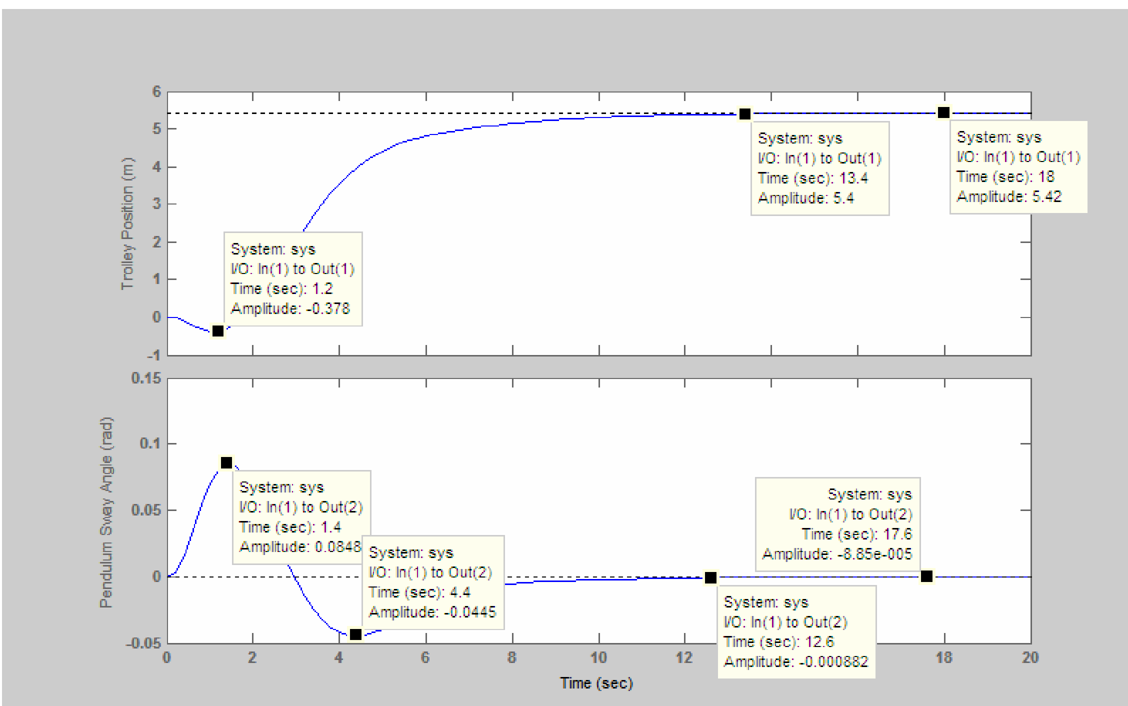


Figure 22 : Response for Controller with m_L=50t

The output when pendulum load mass, m_L used is 500 t is as follows:

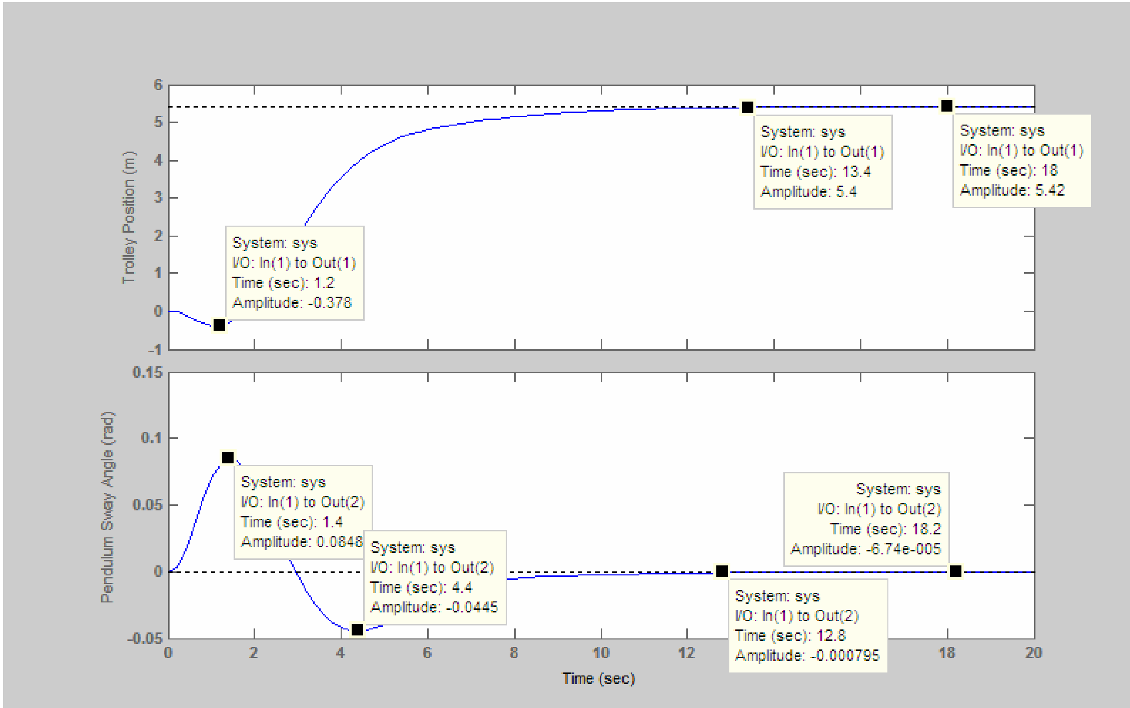


Figure 23 : Response for Controller with m_L=500t

CHAPTER 4
RESULTS

4.0 RESULTS

4.1 Open Loop Versus Closed- Loop Response

Controller Type / System Performance	Open-Loop System (Refer Figure 10 and 11)		Closed-Loop System (Refer Figure 13)	
	Output 1, x_T	Output 2, $\emptyset$	Output 1, x_T	Output 2, $\emptyset$
Overshoot Amplitude	-	-	6.45 m	0.113 rad
Settling Time	-	-	15.2 s	12.7 s
Steady-State Amplitude	Positive Infinity	Negative Infinity	-8.39 m	0.00203 rad

Table 1: Open Loop Versus Closed- Loop Response

4.2 Closed-Loop with Integral Action Response Versus Closed-Loop without Integral Action Response

Controller Type / System Performance	Closed-Loop System with Integral Action (refer Figure 13)		Closed-Loop System without Integral Action (refer Figure 16)	
	Output 1, x_T	Output 2, $\emptyset$	Output 1, x_T	Output 2, $\emptyset$
Overshoot Amplitude	0 m	0.0848 rad	6.45 m	0.113 rad
Settling Time	13.6 s	13 s	15.2 s	12.7 s
Steady-State Amplitude	5.42 m	6.25×10^{-8} rad	-8.39 m	0.00203 rad

Table 2: Closed-Loop with Integral Action Response Versus Closed-Loop without Integral Action Response

4.3 Trolley Positioning Response with Varying System Parameters

Controller Type / **System Performance**	**Closed-Loop System with Varying Pendulum Cable Length, *l*(metres) (refer Figure 17-19)**			**Closed-Loop System with Varying Load Mass, m_L(tonnes) (refer Figure20-23)**			
	$l = 1$	$l = 4$	$l = 8$	$m_L = 0.05$	$m_L = 5$	$m_L = 50$	$m_L = 500$
Overshoot Amplitude (m)	5.65	0	0	0	0	0	0
Settling Time (s)	3.53	7.8	19.2	13.5	13.6	13.4	13.4
Steady-State Amplitude (m)	5.42	5.42	5.42	5.42	5.42	5.42	5.42

Table 3: Trolley Positioning Response with Varying System Parameters

4.4 Sway Angle Response with Varying System Parameters

Controller Type / **System Performance**	**Closed-Loop System with Varying Pendulum Cable Length, *l* (metres) (refer Figure17-19)**			**Closed-Loop System with Varying Load Mass, m_L (tonnes) (refer Figure 20-23)**			
	$l = 1$	$l = 4$	$l = 8$	$m_L = 0.05$	$m_L = 5$	$m_L = 50$	$m_L = 500$
Overshoot Amplitude (rad)	0.937	0.178	0.0553	0.085	0.085	0.085	0.085
Settling Time (s)	3.59	10.2	17.4	12.9	12.8	12.6	12.8
Steady-State Amplitude (rad)	1.75×10^{-5}	7.12×10^{-5}	4.39×10^{-5}	1.42×10^{-5}	1.77×10^{-4}	8.85×10^{-5}	8.74×10^{-5}

Table 4: Sway Angle Response with Varying System Parameters

CHAPTER 5
DISCUSSIONS

5.0 DISCUSSIONS

5.1 Comparison between Open-Loop and Closed-Loop Response

From the output shown from the simulation, the open loop system responses are negative infinity for the sway angle system and positive infinity for the trolley position system. This indicates that when the trolley has started moving forward, pendulum sways backward to the negative angle side till simulation running time ends and so does the trolley travelling system has travelled for infinity since there is no control signals to control the variables into achieving desired values.

When feedback gains are incorporated into the system, the established closed-loop system shows some improvement. The trolley moves forward after the input force is applied until reaching an overshoot of 6.45 m rather than the required 5.42 m only before moves backward to -8.39 m and stops there. The pendulum sways up to 0.113 radian which is 6.5^o at certain instantaneous period and then reduces to only 0.12^o until the trolley stops. This means this closed-loop system still exhibits large percentage overshoot which is 19% and large steady-state error for trolley positioning as well as large overshoot sway angle.

5.2 Comparison between Open-Loop and Closed-Loop Response with Integral Action

Integral action is incorporated into the closed-loop system to reduce the large steady-state error for trolley position. Table 1 shows that the position overshoot is greatly reduced to 0 m and overshoot sway angle is also reduced from 6.5^o to 4.9^o. Final trolley position shows significant improvement from negative trolley position, -8.39 m to the exact desired position which is 5.42 m. Final sway angle also shows negligible value which can be considered 0^o as desired as well as settling time of the system that shows a little improvement for trolley positioning system. This implies that the integral gain implemented into the system has effectively reduced all steady-state error.

5.3 Analysis on the Effect of Varying Pendulum Cable Length, *l*

Figure 17, 18 and 19, show that this controller is able to position the trolley accurately without overshoot with longer pendulum cable length but the settling time to desired value takes longer period than if using shorter cable Shorter cable length also causes very large sway angle which is 53.7^o overshoot for l = 1 m. Like the trolley position response, the crane with more oscillatory response takes longer time to settle to 0^o compared with system with less oscillatory response. This is because the controller induces larger gain to settle down the oscillatory part of system than smaller gain in less oscillatory system. Less oscillatory system exhibits smooth response and longer settling time because of the smaller gain needed. All system with varying cable length studied achieves final value accurately.

5.4 Analysis on the Effect of Varying load mass, m_L

Varying load mass, m_L does not really affected the system response. All values is almost constant with all varying load mass used. This shows that load mass is not a parameter that cause significant impact to this gantry crane controller system. However, other factors have to be taken into account in real industry application such as the rail, trolley and hook strength. Excessive ratio of load mass,m_L to trolley mass, m_T can cause failure and accident.

CHAPTER 6
CONCLUSION

6.0 CONCLUSION

The state-variable feedback controller designed for the Final Year Project has successfully met the main objectives which are to design a control system for the gantry crane to meet the requirement of minimizing sway angle and accurate load positioning. It is able to achieve the desired outputs which are desired trolley position, x_T specified by operator and 0^o final sway angle as well as transient requirement specified which is 10% overshoot.

However, the applicability of this controller to the actual gantry crane system depends on the mechanism used to produce the control signal. If the varying load mass or cable length needs too small or too high of a control gain to give the desired output, than the mechanism that generates control signal has to have the ability to generate that range of gain to the system. From the analysis of varying parameters, it shows that the system response is more sensitive towards the changes of pendulum cable length,l than load mass, m_L. This is because the cable length directly affects the natural frequency of the system which then affects the feedback gain.

CHAPTER 7
RECOMMENDATION

7.0 RECOMMENDATION

Step input is used for this controller as a basis reference input to verify that this controller is reliable to respond to an input of 1 kN force. Towards the end of study, this controller is proven to be able to exhibit the right trend of desired output of fourth order system. Further study should account for real value of input where a motor simulation for the system should be included in the controller.

In achieving desired position of trolley with 0^o sway angle, further study should monitor closely the trolley velocity trend. The maximum velocity achieved by trolley should not exceed 3.04 m/min as stated in crane specification. Also, the author suggests to incorporate a derivative action into the controller to further eliminate current sway angle overshoot which is 4.9^o.

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APPENDICES

Appendix A : MATLAB Program that Converts System in State-Space to Transfer Function

```
clear

clf
mT=0.11;
m=1;
l=6.5;
g=9.81;
b=0.57;

A = [0 1 0 0; 0 -b/mT -(m*g)/mT 0; 0 0 0 1;  0 b/(mT*l)
((mT+m)*g)/(mT*l) 0 ]
B = [0; 1/mT; 0; -1/(mT*l)]

C = [1 0 0 0;0 0 1 0]
D = [10; 0]
[num,den]=ss2tf(A,B,C,D)
```

Appendix B : MATLAB Program used to Determine Feedback Gain of Closed-Lop System

```
clear

clf
mT=0.11;
m=1;
l=6.5;
g=9.81;
b=0.57;

A = [0 1 0 0; 0 -b/mT -(m*g)/mT 0; 0 0 0 1;  0 b/(mT*l)
((mT+m)*g)/(mT*l) 0 ]
B = [0; 1/mT; 0; -1/(mT*l)]

C = [1 0 0 0;0 0 1 0]
D = [10; 0]
[num,den]=ss2tf(A,B,C,D)
pos=10
z=(-log(pos/100))/(sqrt(pi^2+(log(pos/100))^2));
wn=sqrt(g/l);
[num,den]=ord2(wn,z);
r=roots(den);
poles=[r(1) r(2) -18 -20]
K = place(A, B, poles)
```

Appendix C : MATLAB Program for Closed-Loop System with Integral Action

```
clear


mT=0.11;
m=500;
l=6.5;
g=9.81;
b=0.57;

A = [0 1 0 0; 0 -b/mT -(m*g)/mT 0;0 0 0 1;0 b/(mT*l) ((mT+m)*g)/(mT*l)
0 ]
B = [0;1/mT;0;-1/(mT*l)]
C=[1 0 0 0;0 0 1 0];
D=[5.42;0]


Aa=[0 1 0 0 0;zeros(4,1) A]
Ba=[-D;0;0;0]
Bau=[0;B]
Ca=[zeros(2,1) C]
Da=[0;0]

M1=[Bau Aa*Bau (Aa^2)*Bau (Aa^3)*Bau (Aa^4)*Bau]
rank(M1)

pos=10
z=(-log(pos/100))/(sqrt(pi^2+(log(pos/100))^2));
wn=sqrt(g/l);

pr=-z*wn;
pi=wn*sqrt(1-(z^2));
p1=pr+(pi*i)
p2=pr-(pi*i)


[num,den]=ord2(wn,z);
r=roots(den);
poles=[p1 p2 pr*2 (pr*2)+1 pr*10]
K = acker(Aa, Bau, poles)
A1 = Aa-Bau*K;
sys = ss(A1,Ba,Ca,Da);

t=20
step(sys,t)
```

Appendix D : System Parameters from Industry