Palestine Polytechnic University

College of Engineering and Technology

Mechanical Engineering Department

Mechatronics Engineering

ROBOTIC BEAM CART PENDULUM BALANCING SYSTEM

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Hebron-Palestine

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Palestine Polytechnic University

(PPU)

Hebron-Palestine

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Project Team

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According to the project supervisor and according to the agreement of the testing committee members, this project is submitted to the Department of Mechanical Engineering at college of engineering and technology in partial fulfillment of the requirements of the bachelor's degree.

Department Head Signature

Supervisor Signature

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Name:

June-2009

ROBOTIC BEAM CART PENDULUM

BALANCING SYSTEM

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Abd alrahman Herbawi Alaa' alsaheb

Supervisor:

Dr. Yousef Al-Sweiti

Graduation Project

Submitted to the faculty of mechanical engineering department in college of engineering and technology in Palestine polytechnic university.

In partial fulfillment of the requirements for the degree of bachelor of mechanical engineering of Mechatronics major.

Palestine Polytechnic University

Hebron-Palestine

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Dedication

To Palestine polytechnic university

To our instructors

To our families

To our colleagues

Special thanks to all of them

Acknowledgement

Special thanks to our university that supported us, and guided us through the way.

Special thanks to our doctor Dr.Yousef Sweiti that helped us in every aspect of the project, and guided us to accomplish this introduction.

Finally, our best regards to all whom helped us in this introduction of the project.

ABSTRACT

ROBOTIC BEAM CART PENDULUM BALANCING SYSTEM

Working team:

Abd alrahman Herbawi Alaa' alsaheb

Palestine polytechnic university-2008

Supervisor:

Dr. Yousef Al-Sweiti

The purpose of this project is to apply different control methods on a real nonlinear system composed of a cart-carrying-pendulum running over a swinging beam. The different control methods that will be used in the project can be extended and applied over a wide range of industrial fields especially in industrial robots, the output of this project is to position the cart at the desired location on the beam with minimum period of time, taking into consideration to minimize the oscillation of the pendulum, the challenge of this project is to control the cart and specially the pendulum without direct connection with the motor, the cart and the pendulum controlled only by changing the angle of the beam due to the controller command , an ultrasonic sensor will be used to measure the location of the cart, and another two rotational sensors will be used to measure the angle of the beam and pendulum.

This project will be placed later on at the Mechatronics lab to allow the students to execute experiments related to stabilizing nonlinear systems.

In this project the mathematical model will be derived for the system, also all mechanical and electrical components will be totally described with the required simulation for the outputs of the system.

Table of contents

List of Tables

List of Figures

Introduction

As a Mechatronics students, it was very important to us to choose a project that will allow us to apply control methods that we have learned, when this project was chosen there were two main reasons, the first one is as it was previously mentioned that this idea will allow us to apply control methods, the second one is that this project will help the students in the future to see how control methods are applied to stabilize systems.

As shown in Figure 1 ROBOTIC BEAM CART PENDULUM BALANCING SYSTEM consists of cart carrying pendulum swinging on the beam, the angle of the beam is controlled by the torque applied to it by servo motor through the pulleys shown in the same figure, this system is open loop unstable so feedback signals are required to stabilize it, the feedback system consists of one ultrasonic sensor that sends signal to determine the position of the cart, and two rotational sensors that determine the angle of the beam and pendulum.

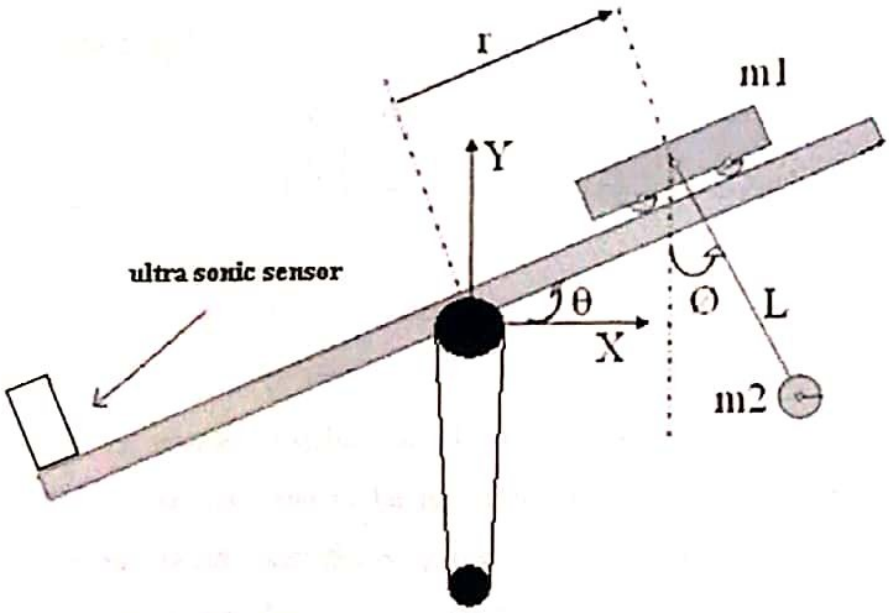


Figure 1 Complete system.

The output of this project is to position the cart at specific location, taking into consideration that the pendulum motion must be quenched at shortest period of time.

In this report the mathematical model and all equations of motion that describes the dynamics of the system will be derived, then the type of the controller which has the ability to stabilize the system and maintain the required outputs will be determined, then the report will discuss the mechanical and electrical components that will make the system, finally the experimental results taken from the system will be discussed.

As a start the mechanical system has to be analyzed and a mathematical equations that describes the system have to be derived , the Lagrangian method was our approach to analyze the system, the Lagrangian method indicates that the kinetic energy of the system T, minus its potential energy U is equal to L. In symbols,

$$L = T - U$$

After applying this formula and finding the total potential and kinetic energy, we can apply the Lagrangian equation which indicates that:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = u$$

Where q : θ, Ø, and r

A three nonlinear equation will be evolve from this Lagrangian equation, these nonlinear equations have to be linearized before transforming them into the state space representation, transforming them into the state space is an important step, that will give the one the ability to apply control methods. Before applying any control method, the controllability of the system has to be checked, then a state feedback controller will be designed, this type of controller makes the input depends on the states of the system, this controller may be called regulator for the reason that it makes every state of the system goes back to zero, and by MATLAB many tests will be made theoretically to check the regulator, then after that the controller will be extended to be a full tracking system rather than regulator, this tracking system will allow the user to order the system to have a certain value for a state or number of states, tests will be made by MATLAB and the results will be shown, then an observer will be designed for the reason that our system has three known states and another three unknown states that have to be estimated and that is what the observer will do.

A certain strategy will be followed in order to control the whole system, this strategy will be to:

1- control the beam alone.

2- control the beam with the cart.

3- control the complete system Beam, Cart and Pendulum.

Every thing that was mentioned in this brief introduction will be shown and explained in a detailed way, and each step will be cleared within each chapter.

Project Time Table

The following tables show the steps of preparing the project:

Table 1.1 First semester.

'eek number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
hoosing project																
athering infor- ıation																
lathematical ıodeling																
imulation																
Aechanical de- ign																
Vriting and rinting																

Table 1.2 Second semester.

Week num- ber	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Building the system																
Sensors cali- bration																
Servo motor calibration																
Operating the system																

Project Cost

The following table show the total cost of the project components

Table 1.3 Components Cost.

Component	Price NIS
Ultrasonic sensor	1229
Encoder	670
Potentiometer	100
Bearings	40
Aluminum	30
Aluminum, ploys	495
Taxes for ultrasonic sensor	335
Screws	100
Mechanical design	1800
Sum of the components bought	**4799**
Components already available at the university	
Servo motor	7000
DAQ	6000
Total sum of the project	**17799**

Chapter 1

Modeling of the system

In this chapter three equations will be derived for the system, these equations will completely describe the dynamics of the system, then those equations will be presented in state space model, this model will be the base of the control system.

1.1 Mathematical modeling

The model of the system is shown in Figure 1.1, the way that will be used to analyze the system is the Lagrange approach as this way has many advantages over the other ways.

The Lagrangian is defined as the kinetic energy of the system T, minus its potential energy U. In symbols,

$$L = T - U$$

The nonlinear system has three degrees of freedom θ, Ø, and r as shown, so three different equations should be obtained, using Lagrange equation shown below,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = u,$$

Where q : θ, Ø, and r

Those nonlinear equations will describe the dynamics of the system.

The input of the system will be torque applied to the beam center, and the output will be the position of the cart.

1.1.1 Analysis of the model

To derive the required equations for the system shown in Figure 1.1, the kinetic and potential energy must be computed for the beam, cart, and pendulum.

The following parameters define the system:

m_1 : Mass of the cart, Kg.

m_2 : Mass of the pendulum, Kg.

a : Length of the beam, meter.

L : Length of the rod carrying pendulum, meter.

r : Position of the cart, meters.

Θ : Angle of the beam, radian.

$\emptyset$: Angle of the pendulum, radian.

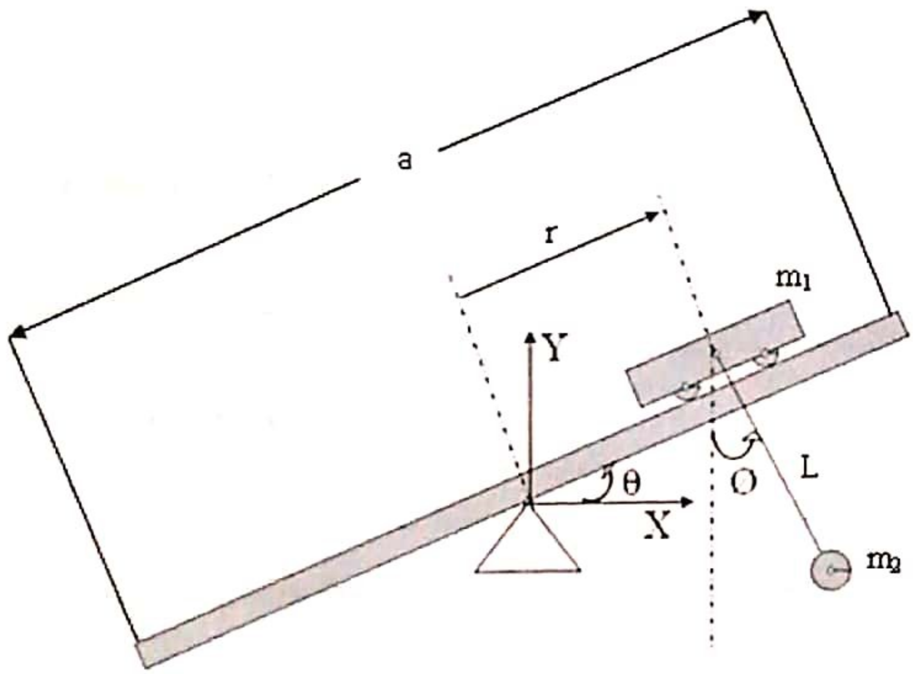


Figure 1.1 Model of the system.

Assumptions for this system

- The kinetic energy of the bearings resulted from rotation are negligible as the bearings are so small.
- The beam is mounted at its center of gravity so its potential energy will be cancelled.
- The friction of the bearings carrying cart is negligible.
- The rod carrying pendulum is mass less.

Now the motion of the three parts of the system beam, cart, and pendulum should be described by the major reference X, Y shown in Figure 1.1.

The motion of the cart m_1, in X and Y axes is

$$x_1 = r\cos\theta \tag{1-1}$$

$$y_1 = r\sin\theta \tag{1-2}$$

Differentiating equations (1-1), and (1-2) will give the velocity of the cart.

in X axis the velocity is

$$\dot{x}_1 = \dot{r}\cos\theta - r\,\dot{\theta}\sin\theta \tag{1-3}$$

And in Y axis will be

$$\dot{y}_1 = \dot{r}\sin\theta + r\,\dot{\theta}\cos\theta \tag{1-4}$$

For the Pendulum the following equations describe its motion

$$x_2 = x_1 + L\sin\varnothing = r\cos\theta + L\sin\varnothing \tag{1-5}$$

$$y_2 = y_1 - L\cos\varnothing = r\sin\theta - L\cos\varnothing \tag{1-6}$$

The velocity of the pendulum in both axes will be:

$$\dot{x}_2 = \dot{x}_1 + L\dot{\emptyset}\cos\emptyset = \dot{r}\cos\theta - r\,\dot{\theta}\sin\theta + L\dot{\emptyset}\cos\emptyset \quad (1\text{-}7)$$

$$\dot{y}_2 = \dot{y}_1 + L\dot{\emptyset}\sin\emptyset = \dot{r}\sin\theta + r\,\dot{\theta}\cos\theta + L\dot{\emptyset}\sin\emptyset \quad (1\text{-}8)$$

1.1.2 Potential Energy:

The total potential energy of the system will be resulted from the motion of the cart, and pendulum. Beam potential energy will be cancelled as it rotates about its center of gravity.

U = potential energy of the cart + potential energy of the pendulum

$$U = m_1 g y_1 + m_2 g y_2$$

$$U = m_1 g\, r\sin\theta + m_2 g(r\sin\theta - L\cos\emptyset) = m_1 g\, r\sin\theta + m_2 g\, r\sin\theta - m_2 g\, L\cos\emptyset \quad (1\text{-}9)$$

1.1.3 Kinetic Energy:

The total kinetic energy of the system will be resulted from the beam, cart, and pendulum motion.

The kinetic energy of the beam is

$$T_{beam} = \frac{1}{2}\, I_b\, \dot{\theta}^2 \quad (1\text{-}10)$$

And for the cart will be

$$T_{cart} = \frac{1}{2} m_1 (\dot{x}_1^2 + \dot{y}_1^2) = \frac{1}{2} m_1 [(\dot{r}\cos\theta - r\,\dot{\theta}\sin\theta)^2 + (\dot{r}\sin\theta + r\,\dot{\theta}\cos\theta)^2]$$

$$= {}^1/_2\, m_1[\dot{r}^2\cos^2\theta - 2\,r\,\dot{r}\;\dot{\theta}\sin\theta\cos\theta + r^2\;\dot{\theta}^2\sin^2\theta + \dot{r}^2\;\sin^2\theta + 2\,r\,\dot{r}\;\dot{\theta}$$

$$\sin\theta\cos\theta + \;r^2\;\dot{\theta}^2\cos^2\theta] = {}^1/_2\, m_1[\dot{r}^2 + r^2\;\dot{\theta}^2\,] \qquad (1\text{-}11)$$

Finally the kinetic energy for the pendulum is

$$T_P = {}^1/_2\, m_2\,(\,\dot{x}_2{}^2 + \dot{y}_2{}^2\,) = {}^1/_2\, m_2\,[\,(\dot{x}_1 + L\,\dot{\varnothing}\cos\varnothing\,)^2 + (\,\dot{y}_1 + L\,\dot{\varnothing}\sin\varnothing\,)^2]$$

$$= {}^1/_2\, m_2\,[\dot{x}_1{}^2 + 2\,\dot{x}_1\,L\,\dot{\varnothing}\cos\varnothing + L^2\,\dot{\varnothing}^2\cos^2\varnothing + \dot{y}_1{}^2 + 2\,\dot{y}_1\,L\,\dot{\varnothing}\sin\varnothing + L^2$$

$$\dot{\varnothing}^2\sin^2\varnothing]$$

Where

$$\dot{x}_1{}^2 = (\,\dot{r}\cos\theta - r\,\dot{\theta}\sin\theta\,)^2 = \dot{r}^2\cos^2\theta - 2\,r\,\dot{r}\;\dot{\theta}\sin\theta\cos\theta + r^2\;\dot{\theta}^2\sin^2\theta$$

$$\dot{y}_1{}^2 = (\;\dot{r}\;\;\sin\theta + r\,\dot{\theta}\cos\theta\,)^2 = \dot{r}^2\;\sin^2\theta + 2\,r\,\dot{r}\;\dot{\theta}\sin\theta\cos\theta + \;r^2\;\dot{\theta}^2\cos^2\theta$$

So T_P becomes

$$T_P = {}^1/_2\, m_2\,[\,\dot{r}^2\cos^2\theta - 2\,r\,\dot{r}\;\dot{\theta}\sin\theta\cos\theta + r^2\;\dot{\theta}^2\sin^2\theta + 2(\dot{r}\cos\theta - r\dot{\theta}\sin\theta\,)$$

$$L\dot{\varnothing}\cos\varnothing + L^2\;\;\dot{\varnothing}^2\cos^2\varnothing + \dot{r}^2\;\sin^2\theta + 2\,r\,\dot{r}\;\dot{\theta}\sin\theta\cos\theta + \;r^2\;\dot{\theta}^2\cos^2\theta$$

$$+ 2(\dot{r}\;\;\sin\theta + r\,\dot{\theta}\cos\theta\,)\,L\dot{\varnothing}\sin\varnothing + L^2\,\dot{\varnothing}^2\;\;\sin^2\varnothing\,]$$

$$T_P = {}^1/_2\, m_2\,[\,\dot{r}^2\cos^2\theta + r^2\;\dot{\theta}^2\sin^2\theta + 2(\dot{r}\cos\theta - r\,\dot{\theta}\sin\theta\,)\,L\dot{\varnothing}\cos\varnothing + L^2\,\dot{\varnothing}^2$$

$$\cos^2\varnothing + \dot{r}^2\;\sin^2\theta + \;r^2\;\dot{\theta}^2\cos^2\theta + 2(\dot{r}\;\;\sin\theta + r\,\dot{\theta}\cos\theta\,)\,L\dot{\varnothing}\sin\varnothing$$

$$+ L^2\,\dot{\varnothing}^2\;\;\sin^2\varnothing\,]$$

$$T_P = {}^1/_2\, m_2\,[\,\dot{r}^2\cos^2\theta + r^2\;\dot{\theta}^2\sin^2\theta + 2(\dot{r}\cos\theta - r\,\dot{\theta}\sin\theta\,)\,L\,\dot{\varnothing}\cos\varnothing + \dot{r}^2$$

$$\sin^2\theta + r^2\dot{\theta}^2\cos^2\theta + 2(\dot{r}\;\;\sin\theta + r\,\dot{\theta}\cos\theta\,)\,L\dot{\varnothing}\sin\varnothing + L^2\,\dot{\varnothing}^2\;\,]$$

$$T_P = \tfrac{1}{2}\, m_2\, [\dot{r}^2 + r^2\, \dot{\theta}^2 + 2\, \dot{r}\, \dot{\emptyset}\, L \cos\theta \cos\emptyset - 2\, r\, \dot{\emptyset}\, L\dot{\theta} \sin\theta \cos\emptyset + 2\, \dot{r}\, \dot{\emptyset}\, L \sin\theta \sin\emptyset + 2\, r\, \dot{\theta}\, \dot{\emptyset}\, L \cos\theta \sin\emptyset + L^2 \dot{\emptyset}^2\,] \quad (1\text{-}12)$$

Now the total kinetic energy is

$T_{Total} = T_{pendulum} + T_{beam} + T_{cart}$

From equations (1-10), (1-11), and (1-12) we get

$$T_{Total} = \tfrac{1}{2}\, m_2\, [\dot{r}^2 + r^2\, \dot{\theta}^2 + 2\, \dot{r}\, \dot{\emptyset}\, L \cos\theta \cos\emptyset - 2\, r\, \dot{\emptyset}\, L\dot{\theta} \sin\theta \cos\emptyset + 2\, \dot{r}\, \dot{\emptyset}\, L \sin\theta \sin + 2\, r\, \dot{\theta}\, \dot{\emptyset}\, L \cos\theta \sin\emptyset + L^2 \dot{\emptyset}^2\,] + \tfrac{1}{2}\, I_b\, \dot{\theta}^2 + \tfrac{1}{2}\, m_1\, [\dot{r}^2 + r^2\, \dot{\theta}^2\,]$$

$$T_{Total} = \tfrac{1}{2}\, m_2\, \dot{r}^2 + \tfrac{1}{2}\, m_2\, r^2\, \dot{\theta}^2 + m_2\, \dot{r}\, \dot{\emptyset}\, L \cos\theta \cos\emptyset - m_2\, r\, \dot{\emptyset}\, L\dot{\theta} \sin\theta \cos\emptyset + m_2\, \dot{r}\, \dot{\emptyset}\, L \sin\theta \sin\emptyset + m_2\, r\, \dot{\theta}\, \dot{\emptyset}\, L \cos\theta \sin\emptyset + \tfrac{1}{2}\, m_2\, L^2 \dot{\emptyset}^2 + \tfrac{1}{2}\, I_b\, \dot{\theta}^2 + \tfrac{1}{2}\, m_1\, \dot{r}^2 + \tfrac{1}{2}\, m_1\, r^2\, \dot{\theta}^2 \quad (1\text{-}13)$$

1.1.4 Lagrange Equation:

After the total kinetic and potential energy calculated for the system, Lagrangian becomes, L =$\sum$ *Total kinetic Energy*-$\sum$ *Total Potential Energy*

$$= \tfrac{1}{2}\, I_b\, \dot{\theta}^2 + \tfrac{1}{2}\, m_1\, \dot{r}^2 + \tfrac{1}{2}\, m_1\, r^2\, \dot{\theta}^2 + \tfrac{1}{2}\, m_2\, \dot{r}^2 + \tfrac{1}{2}\, m_2\, r^2\, \dot{\theta}^2 + \tfrac{1}{2}\, m_2\, L^2 \dot{\emptyset}^2 + m_2\, \dot{r}\, \dot{\emptyset}\, L \cos\theta \cos\emptyset - m_2\, r\, \dot{\emptyset}\, L\dot{\theta} \sin\theta \cos\emptyset + m_2\, \dot{r}\, \dot{\emptyset}\, L \sin\theta \sin\emptyset + m_2\, r\, \dot{\theta}\, \dot{\emptyset} L \cos\theta \sin\emptyset - m_1 g\, r \sin\theta - m_2\, g\, r \sin\theta + m_2\, g\, L \cos\emptyset \quad (1\text{-}14)$$

Equation (1-14) is the base which the three equations that describes the dynamics of the system will be derived from.

The first equation will be

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right)-\frac{\partial L}{\partial \theta}=u \qquad (1\text{-}15)$$

Where u: input torque.

And

$$\frac{\partial L}{\partial \theta} = m_2 L \dot{r} \ \dot{\emptyset} \ \cos \emptyset \sin\theta - m_2 L r \ \dot{\emptyset} \ \dot{\theta} \cos\emptyset \cos \theta + m_2 L \dot{r} \ \dot{\emptyset} \ \sin\emptyset \ \cos \theta - m_2 L r \ \dot{\emptyset} \ \dot{\theta} \sin \emptyset \sin \theta - m_1 g r\cos \theta - m_2 g r \cos \theta + 0 \qquad (1\text{-}16)$$

And

$$\frac{\partial L}{\partial \dot{\theta}} = I \dot{\theta} + 0 + m_1 r^2 \dot{\theta} + 0 + m_2 r^2 \dot{\theta} + 0 + 0 - m_2 L r \dot{\emptyset} \sin \theta \cos\emptyset + 0 + m_2 L r \dot{\emptyset} \sin\emptyset \cos\theta - 0 - 0 - 0 \qquad (1\text{-}17)$$

And

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) = I \ddot{\theta} + m_1 r^2 \ddot{\theta} + 2m_1 r \dot{r} \ \dot{\theta} + m_2 r^2 \ddot{\theta} + 2m_2 r \dot{r} \dot{\theta} - [\, m_2 L r \dot{\emptyset}(-\dot{\emptyset} \ \sin\theta \sin\emptyset \dot{\theta} \cos\emptyset \cos\theta) + \sin\theta \cos\emptyset (m_2 L r \ddot{\emptyset} + \dot{\emptyset} \ m_2 L \ \dot{r})] + [\, m_2 L r \dot{\emptyset} (-\dot{\theta} \sin\theta \sin\emptyset + \dot{\emptyset} \cos\emptyset \cos\theta) + \sin\emptyset \cos\theta \ (m_2 L \dot{\emptyset} \ \dot{r} + m_2 L r \ddot{\emptyset})$$

$$= I_b \ddot{\theta} + m_1 r^2 \ddot{\theta} + 2m_1 r \dot{r} \dot{\theta} + m_2 r^2 \ddot{\theta} + 2m_2 r \dot{r} \dot{\theta} + m_2 L r \dot{\emptyset}^2 \sin\theta \ \sin\emptyset - m_2 L r \dot{\emptyset} \dot{\theta} \cos\emptyset \cos\theta - m_2 L r \ddot{\emptyset} \ \sin\theta \cos\emptyset - m_2 L \dot{r} \dot{\emptyset} \sin\theta \cos\emptyset - m_2 L r \dot{\emptyset} \dot{\theta} \ \sin\theta \ \sin\emptyset + m_2 L r \dot{\emptyset}^2 \ \cos\emptyset \cos\theta + m_2 L \dot{r} \ \dot{\emptyset} \sin\emptyset \cos\theta + m_2 L r \ddot{\emptyset} \ \sin\emptyset \cos\theta \qquad (1\text{-}18)$$

Now substitute equations (1-16), (1-17), and (1-18) in (1-15) the first equation which describes the motion of the beam becomes

$$I_b\,\ddot{\theta} + m_1 r^2 \ddot{\theta} + 2m_1 r \dot{r}\,\dot{\theta} + m_2 r^2 \ddot{\theta} + 2m_2 r \dot{r}\,\dot{\theta} + m_2 L r\, \dot{\emptyset}^2 \sin\theta \ \sin\emptyset - m_2 L r\, \dot{\emptyset}\, \dot{\theta}\, cos\emptyset\ cos\theta - m_2 L r\, \ddot{\emptyset}\ \sin\theta\ cos\emptyset - m_2 L \dot{r}\, \dot{\emptyset}\, \sin\theta\ cos\emptyset - m_2 L r\, \dot{\emptyset}\, \dot{\theta}\, \sin\theta\ \sin\emptyset + m_2 L r\, \dot{\emptyset}^2\ cos\emptyset\ cos\theta + m_2 L \dot{r}\, \dot{\emptyset}\, \sin\emptyset\ cos\theta + m_2 L r\, \ddot{\emptyset}\ \sin\emptyset\ cos\theta + m_2 L \dot{r}\, \dot{\emptyset}\ \cos\emptyset\ \sin\theta + m_2 L r\ \dot{\emptyset}\ \dot{\theta}\ \cos\emptyset\ \cos\theta - m_2 L \dot{r}\, \dot{\emptyset}\ \sin\emptyset\ \cos\theta + m_2 L r\ \dot{\emptyset}\ \dot{\theta}\ \sin\emptyset\ \sin\theta + m_1 g r \cos\theta + m_2 g r \cos\theta = u$$

Rearrange the previous equation to get

$$I_b\,\ddot{\theta} + m_1 r^2\, \ddot{\theta} + 2m_1 r \dot{r}\,\dot{\theta} + m_2 r^2\, \ddot{\theta} + 2m_2 r \dot{r}\,\dot{\theta} + m_2 L r\, \dot{\emptyset}^2\ \sin\theta\ \sin\emptyset - m_2 L r\, \ddot{\emptyset}\ \sin\theta\ cos\emptyset + m_2 L r\, \dot{\emptyset}^2\ cos\emptyset\ cos\theta + m_2 L r\, \ddot{\emptyset}\ \sin\emptyset\ cos\theta + m_1 g r \cos\theta + m_2 g r \cos\theta = u$$

Finally

$$\ddot{\theta}(I_b + m_1 r^2 + m_2 r^2) + r\dot{r}\,\dot{\theta}\ (2m_1 + 2m_2) + m_2 L r\, \dot{\emptyset}^2\ (\sin\theta\ \sin\emptyset + \cos\theta\ \cos\emptyset) + m_2 L r\, \ddot{\emptyset}(\cos\theta\ \sin\emptyset - \sin\theta\ \cos\emptyset) + g r \cos\theta\ (m_1 + m_2) = u \qquad (1\text{-}19)$$

Using the following mathematical relations:

$\sin(A-B) = \sin A \cos B - \cos A \sin B$

$\cos(A-B) = \cos A \cos B + \sin A \sin B$

Equation (1-19) becomes

$$\ddot{\theta}(I_b + m_1 r^2 + m_2 r^2) + (m_1 + m_2)(2r\dot{r}\,\dot{\theta} + g r \cos\theta) + m_2 L r\, \dot{\emptyset}^2 \cos(\theta - \emptyset) + m_2 L r\, \ddot{\emptyset} \sin(\emptyset - \theta) = u \qquad (1\text{-}20)$$

Equation (1-20) is the nonlinear differential equation which expressed the dynamics of the beam.

The second equation which describes the pendulum dynamics is

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right)-\frac{\partial L}{\partial \phi}=0 \qquad (1\text{-}21)$$

Where

$$\frac{\partial L}{\partial \phi}=0+0+0+0+0+0-m_2\,L\,\dot{r}\,\dot{\emptyset}\,\sin\emptyset\,\cos\theta+m_2\,L\,r\,\dot{\emptyset}\,\dot{\theta}\sin\theta\,\sin\emptyset+m_2\,L\,\dot{r}\,\dot{\emptyset}\,\sin\theta\,\cos\emptyset+m_2\,L\,r\dot{\emptyset}\,\dot{\theta}\,\cos\theta\,\cos\emptyset-0-0-m_2\,g\,L\,\sin\emptyset$$

$$=-m_2\,L\,\dot{r}\,\dot{\emptyset}\,\sin\emptyset\,\cos\theta+m_2\,L\,r\,\dot{\emptyset}\,\dot{\theta}\sin\theta\,\sin\emptyset+m_2\,L\,\dot{r}\,\dot{\emptyset}\,\sin\theta\,\cos\emptyset+m_2\,L\,r\dot{\emptyset}\,\dot{\theta}\,\cos\theta\,\cos\emptyset-m_2\,g\,L\,\sin\emptyset \qquad (1\text{-}22)$$

And

$$\frac{\partial L}{\partial \dot{\phi}}=[0+0+0+0+0+m_2\,L^2\dot{\emptyset}+m_2\,L\,\dot{r}\cos\theta\,\cos\emptyset-m_2\,L\,r\,\dot{\theta}\,\sin\theta\,\cos\emptyset+m_2\,L\,\dot{r}\sin\theta\,\sin\emptyset+m_2\,L\,r\,\dot{\theta}\,\sin\emptyset\,\cos\theta] \qquad (1\text{-}23)$$

And

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right)=m_2\,L^2\ddot{\emptyset}+[m_2\,L\,\dot{r}\,(-\dot{\emptyset}\cos\theta\,\sin\emptyset-\dot{\theta}\cos\emptyset\,\sin\theta)+m_2\,L\,\ddot{r}\,\cos\theta\,\cos\emptyset\,]$$
$$-[\,m_2\,L\,r\,\dot{\theta}(-\dot{\emptyset}\sin\theta\,\sin\emptyset+\dot{\theta}\cos\emptyset\,\cos\theta)+\sin\theta\,\cos\emptyset(\,m_2\,L\,r\,\ddot{\theta}+\dot{\theta}\,m_2\,L\,\dot{r}\,)]+[m_2\,L\,\dot{r}\,(\dot{\theta}\cos\theta\,\sin\emptyset-\dot{\emptyset}\,\sin\theta\,\cos\emptyset)+\sin\emptyset\,\sin\theta\,m_2\,L\,\ddot{r}]+[\,m_2\,L\,r\,\dot{\theta}\,(-\dot{\theta}\sin\theta\,\sin\emptyset+\dot{\emptyset}\,\cos\theta\,\cos\emptyset)+\sin\emptyset\,\cos\theta\,(\,m_2\,L\,\dot{\theta}\,\dot{r}+m_2\,L\,r\,\ddot{\theta}\,)]$$

$$=m_2\,L^2\ddot{\emptyset}-m_2\,L\,\dot{r}\,\dot{\emptyset}\,\cos\theta\,\sin\emptyset-m_2\,L\,\dot{r}\,\dot{\theta}\,\cos\emptyset\,\sin\theta+m_2\,L\,\ddot{r}\,\cos\emptyset\,\cos\theta+m_2\,L\,r\,\dot{\theta}\,\dot{\emptyset}\,\sin\theta\,\sin\emptyset-m_2\,L\,r\,\dot{\theta}^2\cos\emptyset\,\cos\theta-m_2\,L\,r\,\ddot{\theta}\,\sin\theta\,\cos\emptyset-m_2\,L\,\dot{r}\,\dot{\theta}\,\sin\theta\,\cos\emptyset+m_2\,L\,\dot{r}\,\dot{\theta}\,\sin\emptyset\,\cos\theta+m_2\,L\,\dot{r}\,\dot{\emptyset}\,\sin\theta\,\cos\emptyset+m_2\,L\,\ddot{r}\,\sin\theta\,\sin\emptyset-m_2\,L\,r\,\dot{\theta}^2\sin\theta\,\sin\emptyset+m_2\,L\,r\,\dot{\theta}\,\dot{\emptyset}\,\cos\emptyset\,\cos\theta+m_2\,L\dot{r}\,\dot{\theta}\,\sin\emptyset\,\cos\theta+m_2\,L\,r\,\ddot{\theta}\,\sin\emptyset\,\cos\theta \qquad (1\text{-}24)$$

Now substitute equations (1-22), (1-23), and (1-24) in (1-21) the equation which describes the motion of the pendulum is

$$m_2 L^2\ddot{\emptyset} - m_2 L \dot{r}\, \dot{\theta} \cos\emptyset \sin\theta + m_2 L \ddot{r} \cos\emptyset \cos\theta - m_2 L r\, \dot{\theta}^2 \cos\emptyset \cos\theta - m_2 L r\, \ddot{\theta} \sin\theta \cos\emptyset - m_2 L \dot{r}\, \dot{\theta} \sin\theta \cos\emptyset + m_2 L \dot{r}\, \dot{\theta} \sin\emptyset \cos\theta + m_2 L \ddot{r} \sin\theta \sin\emptyset - m_2 L r\, \dot{\theta}^2 \sin\theta \sin\emptyset + m_2 L \dot{r}\, \dot{\theta} \sin\emptyset \cos\theta + m_2 L r\, \ddot{\theta} \sin\emptyset \cos\theta + m_2 g L \sin\emptyset = 0$$

Rearrange the previous equation to obtain

$$m_2 L^2\ddot{\emptyset} + m_2 L \dot{r}\, \dot{\theta} [\sin\emptyset \cos\theta - \cos\emptyset \sin\theta + \sin\emptyset \cos\theta - \cos\emptyset \sin\theta] - m_2 L r\, \dot{\theta}^2 [\cos\theta \cos\emptyset + \sin\theta \sin\emptyset] + m_2 L r\, \ddot{\theta} [\sin\emptyset \cos\theta - \cos\emptyset \sin\theta] + m_2 L \ddot{r} [\cos\theta \cos\emptyset + \sin\theta \sin\emptyset] + m_2 g L \sin\emptyset = 0 \qquad (1\text{-}25)$$

Using the following mathematical relations:

sin(A−B)=sin A cos B − cos A sin B

cos(A−B)=cos A cos B + sin A sin B

Equation (1-25) becomes

$$m_2 L^2\ddot{\emptyset} + 2 m_2 L \dot{r}\, \dot{\theta} \sin(\emptyset - \theta) - m_2 L r\, \dot{\theta}^2 \cos(\emptyset - \theta) + m_2 L r\, \ddot{\theta} \sin(\emptyset - \theta) + m_2 L \ddot{r} \cos(\emptyset - \theta) + m_2 g L \sin\emptyset = 0 \qquad (1\text{-}26)$$

Equation (1-26) is the nonlinear differential equation which expressed the dynamics of the pendulum.

The third equation which describes the cart motion is

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{r}}\right) - \frac{\partial L}{\partial r} = 0 \qquad (1\text{-}27)$$

Where

$$\frac{\partial L}{\partial r} = 0+0+ m_1\, r\,\dot{\theta}^2 + 0+ m_2\, r\,\dot{\theta}^2 - m_2\, L\, \dot{\emptyset}\, \dot{\theta}\, \sin\theta\, \cos\emptyset + m_2\, L\, \dot{\emptyset}\, \dot{\theta}\, \sin\emptyset\, \cos\theta$$

$$- m_1\, g\, \sin\theta - m_2\, g\, \sin\theta + 0$$

$$= + m_1\, r\,\dot{\theta}^2 + m_2\, r\,\dot{\theta}^2 - m_2\, L\, \dot{\emptyset}\, \dot{\theta}\, \sin\theta\, \cos\emptyset + m_2\, L\, \dot{\emptyset}\, \dot{\theta}\, \sin\emptyset\, \cos\theta$$

$$- m_1\, g\, \sin\theta - m_2 g \sin\theta \qquad (1\text{-}28)$$

And

$$\frac{\partial L}{\partial \dot{r}} = 0+m_1\dot{r}+0+ m_2\dot{r}+0 +0+ m_2\, L\, \dot{\emptyset}\, \cos\emptyset\, \cos\theta + m_2\, L\, \dot{\emptyset}\, \sin\emptyset\, \sin\theta\ + 0 + 0 + 0$$

$$+ 0$$

$$= \quad m_1\dot{r} + m_2\dot{r} + m_2\, L\, \dot{\emptyset}\, \cos\emptyset\, \cos\theta + m_2\, L\, \dot{\emptyset}\, \sin\emptyset\, \sin\theta$$

$$= \quad \dot{r}\, (m_1 + m_2) + m_2\, L\, \dot{\emptyset}\, \cos(\emptyset - \theta) \qquad (1\text{-}29)$$

Then

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{r}}\right) = m_1\ddot{r} + m_2\ddot{r} + [m_2\, L\, \dot{\emptyset}(-\dot{\theta}\, \sin\theta\, \cos\emptyset - \dot{\emptyset}\, \sin\emptyset\, \cos\theta) + \cos\theta\, \cos\emptyset\, (m_2\, L$$

$$\ddot{\emptyset})] + [m_2\, L\, \dot{\emptyset}(\dot{\theta}\, \sin\emptyset\, \cos\theta + \dot{\emptyset}\, \sin\theta\, \cos\emptyset) + \sin\theta\, \sin\emptyset\, (m_2\, L\, \ddot{\emptyset})] \qquad (1\text{-}30)$$

Now substitute equations (1-28), (1-29), and (1-30) in (1-27) the equation which describes the motion of the cart becomes

$$m_1\ddot{r} + m_2\ddot{r} - m_2\, L\, \dot{\emptyset}\, \dot{\theta}\, \sin\theta\, \cos\emptyset - m_2\, L\, \dot{\emptyset}^2\ \sin\emptyset\, \cos\theta + m_2\, L\, \ddot{\emptyset}\, \cos\emptyset\ \cos\theta + m_2\, L\, \dot{\emptyset}$$

$$\dot{\theta}\, \sin\emptyset\, \cos\theta + m_2\, L\, \dot{\emptyset}^2\ \sin\theta\, \cos\emptyset + m_2\, L\, \ddot{\emptyset}\ \ \sin\emptyset\ \sin\theta = 0$$

Rearrange the previous equation to obtain

$m_1\ddot{r} + m_2\ddot{r} - m_2 L \dot{\emptyset}^2 \ \sin\emptyset \cos\theta + m_2 L \ddot{\emptyset} \ \ \cos\emptyset \ \cos\theta + m_2 L \dot{\emptyset}^2 \ \sin\theta \cos\emptyset + m_2 L$
$\ddot{\emptyset} \ \ \sin\emptyset \ \sin\theta - m_1 r \dot{\theta}^2 - m_2 r \dot{\theta}^2 + m_1 g \sin\theta + m_2 g \sin\theta = 0$

This equals

$\ddot{r}(m_1 + m_2) + m_2 L \dot{\emptyset}^2 (\sin\theta \cos\emptyset - \sin\emptyset \cos\theta) + m_2 L \ddot{\emptyset} (\cos\emptyset \ \cos\theta - \sin\emptyset \ \sin\theta)$
$- r\dot{\theta}^2 (m_1 + m_2) + g \sin\theta(m_1 + m_2) = 0$

$$(m_1 + m_2)(\ddot{r} - r\dot{\theta}^2 + g \sin\theta) + m_2 L \dot{\emptyset}^2 \sin(\theta - \emptyset) + m_2 L \ddot{\emptyset} \cos(\theta - \emptyset) = 0$$

(1-31)

This nonlinear equation describes the motion of the cart along the beam.

1.2 Linearization

Now the three nonlinear equations (1-20), (1-26), and (1-31), should be linearized about the operating point $\theta = 0, r = 0$ to be able to use the control design strategies of linear time invariant systems.

The following are assumed to linearize each equation:

$$\sin \theta = \theta$$
$$\cos \theta = 1$$
$$\sin \emptyset = \emptyset$$
$$\cos \emptyset = 1$$
$$r = r_0 + \Delta r$$
$$u = u_0 + \Delta u$$

and neglect all nonlinear terms which are square or product terms.

Now apply the previous assumptions to equations (1-20), (1-26), and (1-31) to get the three linearized equations

For equation (1-20), the linearized form is

$$\ddot{\theta}(\, I_b + m_1 r_0^2 + m_2 r_0^2) + (m_1 + m_2)\, g\, \Delta r = \Delta u \qquad (1\text{-}32)$$

For equation (1-26), we get

$$m_2 L^2 \ddot{\emptyset} + m_2 L\, \Delta\, \ddot{r} + m_2 g L \emptyset = 0 \qquad (1\text{-}33)$$

For equation (1-31), we get

$$\Delta\ddot{r}\, (m_1 + m_2) + m_2 L \ddot{\emptyset} + (m_1 + m_2)\, g\, \theta = 0 \qquad (1\text{-}34)$$

1.3 State space representation

Now the three linearized equations (1-32), (1-33), and (1-34) will be represented in state space model, this facilitates the application of control techniques as the system is from the high order.

The general form of the state space representation of the system is:

$$\dot{x} = Ax + Bu \qquad (1\text{-}35)$$

$$y = Cx + Du \qquad (1\text{-}36)$$

Where x : The states of the system (6x1).

A : System matrix (6x6).

B : Input matrix (6x1).

C : Output matrix (3x6)

D : Feed forward matrix.

Y : Output

Now the states of the system are assumed as follow:

$$x_1 = \theta$$

$$x_2 = \dot{\theta} \tag{1-37}$$

$$x_3 = \phi$$

$$x_4 = \dot{\phi} \tag{1-38}$$

$$x_5 = r$$

$$x_6 = \dot{r} \tag{1-39}$$

From (1-37),(1-38), and (1-39) we have

$$\dot{x}_1 = x_2 \tag{1-40}$$

$$\dot{x}_3 = x_4 \tag{1-41}$$

$$\dot{x}_5 = x_6 \tag{1-42}$$

To construct the state space model $\ddot{\theta}, \ddot{\phi}$, and $\ddot{r}$ should be described as a function of the states, from equation (1-32)

$$\ddot{\theta}\left(I_b + m_1 r_0^{\,2} + m_2 r_0^{\,2}\right) = \Delta u - gr(m_1 + m_2)$$

We get:

$$\ddot{\theta} = \frac{\Delta u}{\left(I_b + m_1 r_0^{\,2} + m_2 r_0^{\,2}\right)} - \frac{g(m_1 + m_2)r}{\left(I_b + m_1 r_0^{\,2} + m_2 r_0^{\,2}\right)} \tag{1-43}$$

And from equation (1-33)

$m_2 L^2 \ddot{\phi} + m_2 L \ddot{r} + m_2 g L \phi = 0$, divide by L we have

$$m_2 L \ddot{\phi} = -m_2 \ddot{r} - m_2 g \phi \tag{1-44}$$

Divide by $m_2 L$ to get

$$\ddot{\phi} = \frac{(-m_2\ddot{r} - m_2 g\phi)}{m_2 L} \qquad (1\text{-}45)$$

The third equation (1-34)

$$\ddot{r}(m_1 + m_2) + m_2 L\ddot{\phi} + g\theta(m_1 + m_2) = 0$$

Rearrange the previous equation we get:

$$\ddot{r} = \frac{(-m_2 L\ddot{\phi} - g\theta(m_1 + m_2))}{(m_1 + m_2)} = \frac{-m_2 L\ddot{\phi}}{(m_1 + m_2)} - g\theta \qquad (1\text{-}46)$$

Substitute equation (1-44) in (1-46):

$$\ddot{r} = \frac{-(-m_2\ddot{r} - m_2 g\phi)}{(m_1 + m_2)} - g\theta$$

Rearrange the previous equation we get:

$$\ddot{r} = \frac{m_2}{m_1} g\phi - \frac{(m_1 + m_2)}{m_1} g\theta \qquad (1\text{-}47)$$

Substitute equation (1-46) in (1-44)

$$m_2 L\ddot{\phi} + m_2 \left[\frac{-m_2 L\ddot{\phi}}{(m_1 + m_2)} - g\theta\right] + m_2 g\phi = 0$$

Rearrange the previous equation we get:

$$\ddot{\phi} = \frac{g(m_1 + m_2)}{m_1 L}\theta - \frac{g(m_1 + m_2)}{m_1 L}\phi \qquad (1\text{-}48)$$

Through equations (1-37) - (1-48) the state space model can be constructed as follow:

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

$$y = Cx + Du \quad \text{, where}$$

$$\mathbf{X} = \begin{bmatrix} \theta \\ \dot{\theta} \\ \phi \\ \dot{\phi} \\ r \\ \dot{r} \end{bmatrix} \qquad \dot{X} = \begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ \dot{\phi} \\ \ddot{\phi} \\ \dot{r} \\ \ddot{r} \end{bmatrix}$$

The system matrix will be

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\dfrac{g(m_1+m_2)}{I+m_1r_0^2+m_2r_0^2} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \dfrac{g(m_1+m_2)}{m_1L} & 0 & \dfrac{-g(m_1+m_2)}{m_1L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \dfrac{-g(m_1+m_2)}{m_1} & 0 & \dfrac{gm_2}{m_1} & 0 & 0 & 0 \end{bmatrix}$$

The input matrix is

$$B = \begin{bmatrix} 0 \\ \dfrac{1}{I+m_1r_0^2+m_2r_0^2} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

And the output matrix

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

Feed forward matrix is

$$D = [0]$$

Chapter 2

Control design and Simulation

The system is open loop unstable, therefore a controller should be designed using certain control techniques, which will affect the dynamics of the system, the software that will be used is MATLAB with its Simulink model.

2.1 Stability

In the previous chapter the three equations of motion are derived for the system and described by state space model equations (2-1) and (2-2).

$$\dot{x} = Ax + Bu \tag{2-1}$$

$$Y = Cx + Du \tag{2-2}$$

This system can be described by the Simulink model shown in Figure 2.1

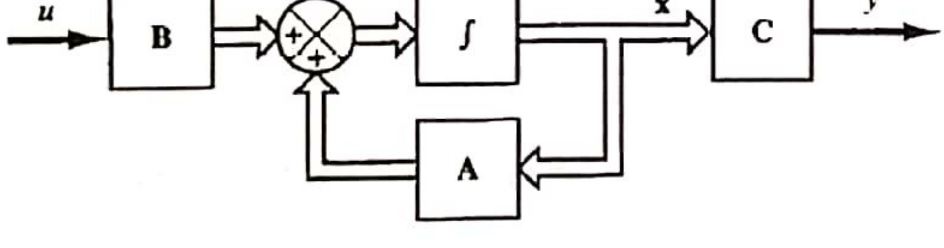


Figure 2.1 Simulink model for open loop system.

With approximate values of $m_1 = 0.745 Kg$, $m_2 = 0.027 Kg$, $L = 0.125 m$ mass of the cart, mass of the pendulum, length of the rod respectively, system matrix $\boldsymbol{A}$ becomes

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\dfrac{g(m_1+m_2)}{I+m_1 r_0^{\,2}+m_2 r_0^{\,2}} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \dfrac{g(m_1+m_2)}{m_1 L} & 0 & \dfrac{-g(m_1+m_2)}{m_1 L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \dfrac{-g(m_1+m_2)}{m_1} & 0 & \dfrac{g m_2}{m_1} & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -34.8680 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1.2707 & 0 & -1.2707 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -10.1655 & 0 & 0.3555 & 0 & 0 & 0 \end{bmatrix}$$

For the input matrix $\boldsymbol{B}$ we should calculate the moment of inertia of the swinging aluminum beam and the pulleys about the axis shown in Figure 2.2.

Use the Kinetic energy to compute this value, knowing that $\omega_s = 2\omega_{Beam}$,and the mass of the sensor and its counter weight is included in m_c

$$KE = \frac{1}{2} I_{Beam}\,\omega_{beam}^2 + \frac{1}{2} I_{l\arg epully}\,\omega_{beam}^2 + \frac{1}{2} I_{smallpully}\,\omega_s^2$$

$$KE = \frac{1}{2}[I_{Beam} + I_{l\arg epully} + 4{*}I_{smallpully}]\omega_{beam}^2$$

$$KE = \frac{1}{2}[I_{Total}]\omega_{beam}^2$$

$$I_{beam} = \frac{1}{12} * 2 * m_b * a^2 + 2 * m_c * \left(\frac{a}{2}\right) \tag{2-3}$$

$$= \frac{1}{12} * 2 * 1.04 * 0.7^2 + 2 * .48 * .37^2 = 0.2164\, Kg.m^2$$

$$I_{l\arg epully} = \frac{1}{2} m_1 R_1^2 = \frac{1}{2} * .265 * .077^2 = 7.86 * 10^{-4}$$

$$I_{smallepull\,y} = \frac{1}{2} m_2 R_2^2 = \frac{1}{2} * .075 * .037^2 = 5.13 * 10^{-5}$$

$$I_{Total} = .2164 + 7.86 * 10^{-4} + 5.13 * 10^{-5} = .2172\, Kg.m^2$$

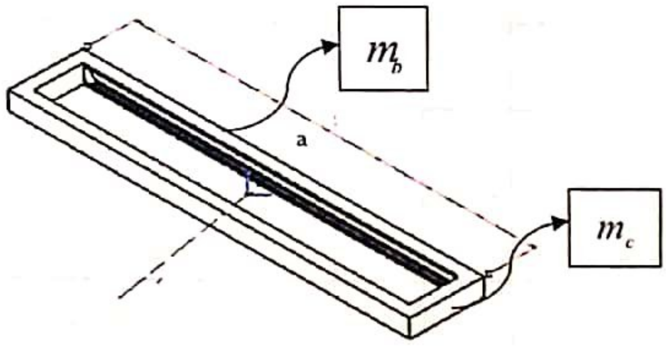


Figure 2.2 Beam shape.

Now input matrix $\boldsymbol{B}$ assuming position of the cart $r_0 = 0.0$m will be

$$\mathbf{B} = \begin{bmatrix} 0 \\ \dfrac{1}{I + m_1 r_0^2 + m_2 r_0^2} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 4.6041 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The stability of this system has to be checked, the system will be stable if all its poles (Eigenvalues) are located at the left side of the s-plane.

Eigenvalues of the system is the roots of $|s\boldsymbol{I} - \boldsymbol{A}|$

Roots$|s\boldsymbol{I} - \boldsymbol{A}|$ = Eigen values

Using MATLAB with the following function:

```
>> eig(A)
```

we get the Eigenvalues

ans = -4.3366,

4.3366,

-0.0000 + 4.3417i,

-0.0000 - 4.3417i,

0.0000 + 1.1073i,

0.0000 - 1.1073i

One can notice that the system is unstable, simulation of the system shown in Figure 2.1 with varying initial conditions, will give us information about the dynamics of the open loop system.

The system shown in Figure 2.1 is constructed and simulated using MATLAB program with zero torque input as in Figure 2.3, Gray is the real system, and the green block is the input.

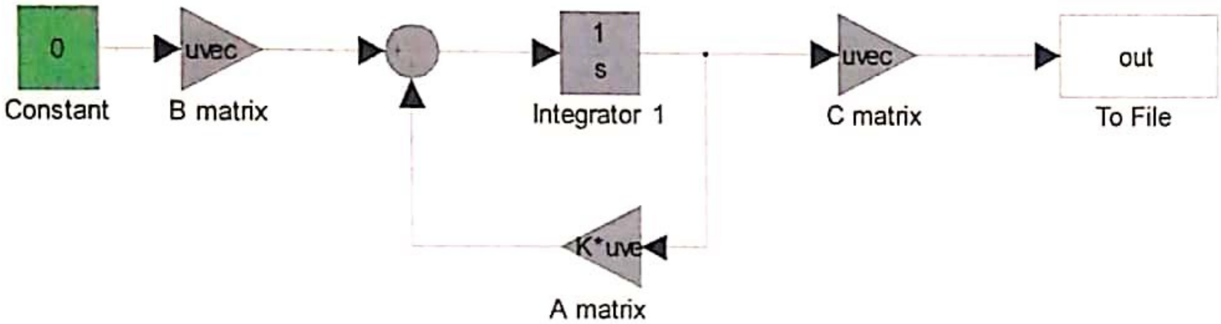


Figure 2.3 MATLAB Simulink model for open loop system.

And the responses will be as follows:

Case1 assuming that all initial conditions equal zero except r = 5cm, the outputs are shown in the following figure:

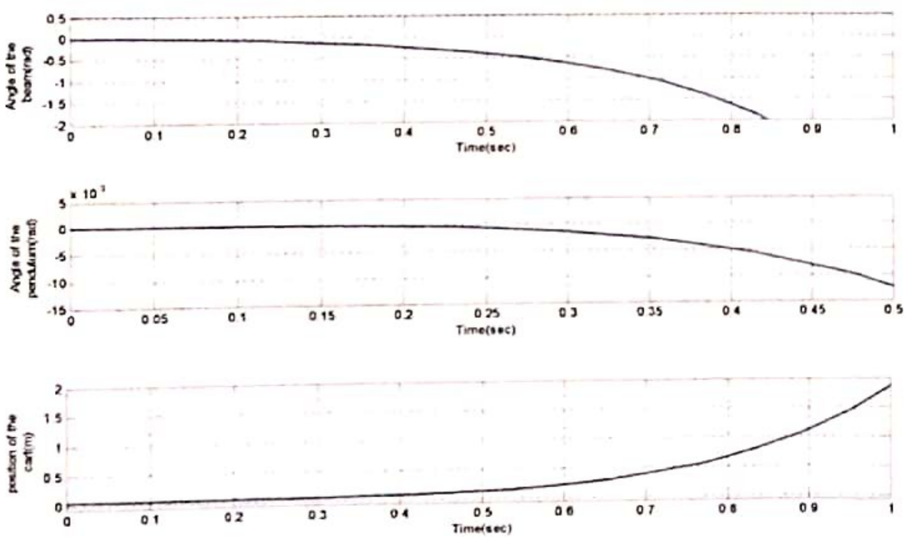


Figure 2.4 Open loop response with initial condition r = 5cm.

Figure 2.4 shows that when the cart positioned at distance r = 5cm as an initial condition, the beam will fall in clock wise direction also the cart will go away from the center as shown. The pendulum will oscillate in random way that depends on the motion of the cart and the beam, so the system is unstable with infinite output response.

Case 2 Now assume that the angle of pendulum $\emptyset=\pi/18$, system response is shown in Figure 2.5

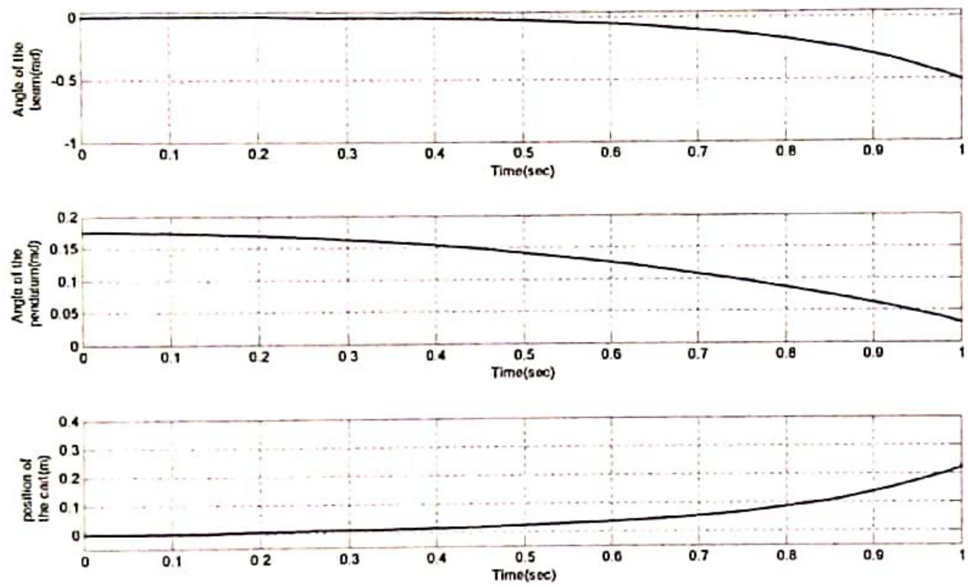


Figure 2.5 Open loop response with initial condition $\emptyset=\pi/18$.

In this case the angle of the pendulum changed by 10 degrees, the pendulum starts to oscillate this force the beam to fall in counterclockwise direction as shown, also the cart will go away from the center of the beam, so this is an unstable system.

Case 3 Now assume that the angle of pendulum Ø=π/18, and the position of the cart r =5cm the responses are shown in Figure 2.6

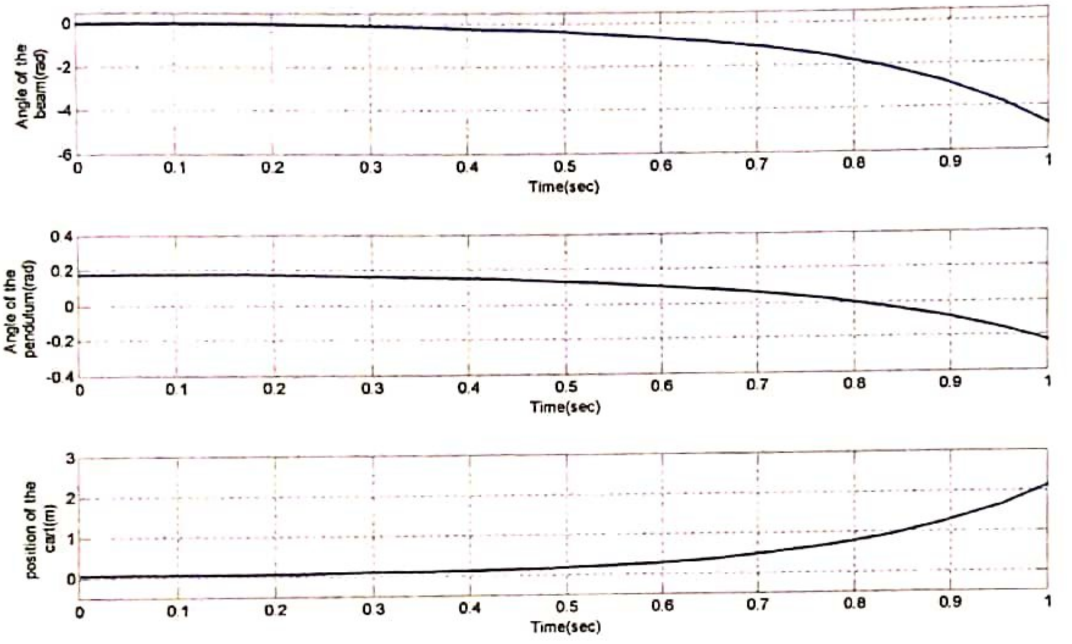


Figure 2.6 Open loop response with initial condition Ø=π/18, and r =5cm.

The previous initial conditions will force the beam to fall and the cart to go away, the three previous cases show that the outputs will go to an infinite values, so the system is unstable and needs to be controlled to reach values determined by the user.

2.2 State Controllability:

As we see a controller is needed to stabilize the system, before that the system must be checked if it is able to be controlled by a controller, the system is said to be completely controllable if it is possible to construct an unconstrained control vector u(t) that will transfer any given initial output $x(t_0)$ to any final output $x(t_1)$ in a finite time interval $t_0 \leq t \leq t_1$, to check the controllability of the system a matrix should be constructed from the system and input matrix.

The controllability matrix = $[B, AB, A^2B, A^3B, \text{------} A^{n-1}B]$,

where n: is the number of the states of the system.

In our system n = 6 so controllability matrix will be :

$$\text{Controllability matrix} = [B, AB, A^2B, A^3B, A^4B, A^5B] \tag{2-4}$$

If the system is controllable the rank of the controllability matrix should be equal to the number of the states of the system, in our system rank must equal six.

Using MATLAB function **ctrb**

```
>> Co=ctrb(A,B)
```

$$\mathbf{Co} = 10^3 \begin{bmatrix} 0 & 0.0046 & 0 & 0 & 0 & 1.6319 \\ 0.0046 & 0 & 0 & 0 & 1.6319 & 0 \\ 0 & 0 & 0 & 0.0059 & 0 & -0.0074 \\ 0 & 0 & 0.0059 & 0 & -0.0074 & 0 \\ 0 & 0 & 0 & -0.0468 & 0 & 0.0021 \\ 0 & 0 & -0.0468 & 0 & 0.0021 & 0 \end{bmatrix}$$

Now calculate the rank of this matrix using MATLAB with the function **rank**

```
>> rank(Co)
```

ans = 6 , so the system is controllable.

2.3 Controller Design

The type of the controller that will be applied to the system is the state feed-back controller via pole placement, the nature of state feedback controller is to make the input control signal (u) depends on the states of the system, assume that all states of the system are measured and available for feedback, the poles of the closed loop system may be placed at any desired location through an appropriate state feedback gain matrix, based on transient response damping ratio, speed, and steady state requirements, provided that the system is completely state controllable (checked in the previous section).

Design steps for pole placement:

The system equation is

$$\dot{x} = Ax + Bu \tag{2-5}$$

And the control input signal

$$u = -Kx \tag{2-6}$$

The feedback gain matrix **K** that will be determined by the new required poles and stabilize the system, will be calculated as follows assume the system is controllable,

Step 1: From the polynomial compute $a_1 \dots a_n$

$$|s\mathbf{I} - \mathbf{A}| = s^n + a_1 s^{n-1} + \dots + a_{n-1}s + a_n$$

In our system

$$|s\mathbf{I} - \mathbf{A}| = s^6 + a_1 s^5 + a_2 s^4 + a_3 s^3 + a_4 s^2 + a_5 s + a_6 \tag{2-7}$$

Step 2: Compute the transformation matrix $\mathbf{T}$ that transforms the system state equation into controllable canonical form

$$\mathbf{T} = \mathbf{MW} \tag{2-8}$$

Where:

$$\mathbf{M} = \begin{bmatrix} \mathbf{B} & \mathbf{AB} & \dots & \mathbf{A}^{n-1}\mathbf{B} \end{bmatrix} \tag{2-9}$$

$$\mathbf{W} = \begin{bmatrix} a_{n-1} & a_{n-2} & \cdots & a_1 & 1 \\ a_{n-2} & a_{n-3} & \cdots & 1 & 0 \\ \vdots & \vdots & & \vdots & \vdots \\ a_1 & 1 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \end{bmatrix} \tag{2-10}$$

Step 3:Determine the desired characteristic polynomial using the desired poles

$$(s - p_1)(s - p_2)(s - p_3)\dots(s - p_n) = s^n + \alpha_1 s^{n-1} + \dots + \alpha_{n-1} s + \alpha_n$$

We have

$$(s - p_1)(s - p_2)(s - p_3)(s - p_4)(s - p_5)(s - p_6) = s^6 + \alpha_1 s^5 + \alpha_2 s^4 + \alpha_3 s^3 + \alpha_4 s^2 + \alpha_5 s^1 + \alpha_6 \tag{2-11}$$

Now the gain matrix $\mathbf{K}$ will be

$$\mathbf{K} = \begin{bmatrix} \alpha_n - a_n & \vdots & \alpha_{n-1} - a_{n-1} & \vdots & \dots & \vdots & \alpha_2 - a_2 & \vdots & \alpha_1 - a_1 \end{bmatrix} \mathbf{T}^{-1} \tag{2-12}$$

The previous calculations can be easily done using MATLAB using the following function

```
>> K=place(A,B,P)
```

Where $P= [P_1\text{--------}P_n]$ (desired poles)

Substituting equation (2-3) in (2-1) gives the new state space model:

$$\dot{\mathbf{x}} = (\mathbf{A} - \mathbf{BK})\mathbf{x} \tag{2-13}$$

$$Y = Cx \tag{2-14}$$

This is the new closed loop controlled system shown in Figure 2.7, note that all the states of this system is fed back to input signal (u), now let's check the stability of this system, Poles or Eigenvalues are the roots of $|sI - A + BK|$, assume desired poles P = [-1+1i,-1-1i,-5,-6,-6.1,-6.2], this means that the damping ratio for the system $\xi = 0.7$, the settling time T_s= 4 seconds, those values may be changed in order to enhance the response of the system with taking into consideration that the maximum value of the input must not exceed the maximum allowable torque of the servo motor. Also the same values for system and input matrices are assumed.

Using MATLAB with the following functions we get matrix K, and the poles of the new system

>> K=place(A,B,P)

We get

$$K = 10\text{^}3[0.0819 \quad 0.0066 \quad -1.4876 \quad -0.9948 \quad -0.3823 \quad -0.1769 \ ]$$

>> eig(A-B*K)

We get

Ans =

-10.9283 + 3.7043i

-10.9283 - 3.7043i

-3.9867 + 6.1511i

-3.9867 - 6.1511i

-0.2399 + 1.7170i

-0.2399 - 1.7170i

This is a stable system with all of its poles at the left side plan as determined.

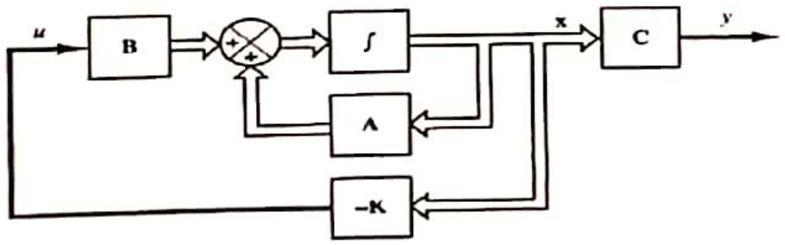


Figure 2.7 Closed loop system with state feedback controller.

Simulation of the complete system shown in Figure 2.7, will show that the system tends to make the outputs reach zero, this means that any disturbances of the system will be regulated by the controller.

Case1 assuming that all initial conditions equal zero except r =5cm, the responses are shown in Figure 2.8:

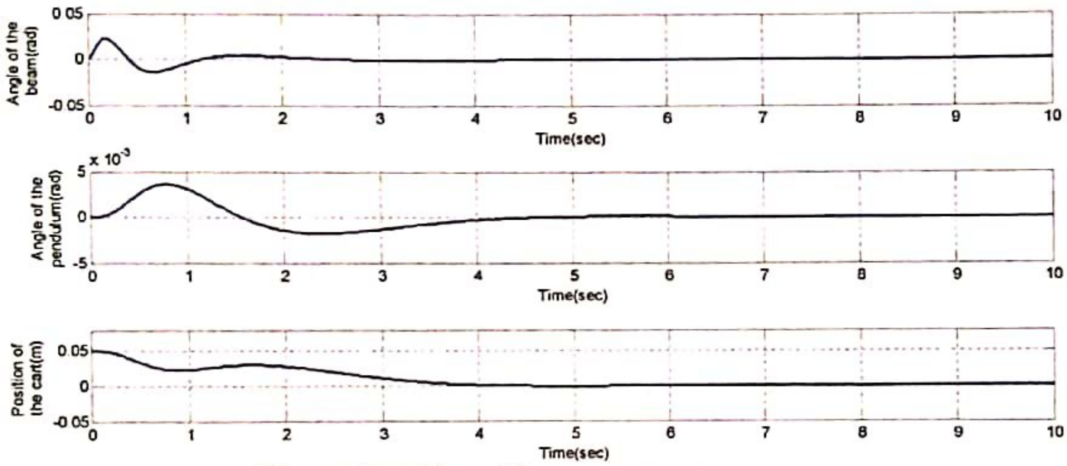


Figure 2.8 Closed loop response.

In the previous case the system tends to return the cart to the zero position, so the system forces the beam to rotate two degrees clockwise then back to zero then another two degrees counter clock wise this move the cart to the desired position and makes the pendulum to oscillate as shown in the previous figure, finally the steady state of the three outputs reach zero after about 4.5 seconds.

Case 2 assuming that all initial conditions equal zero except Ø=π/18, the response is shown in Figure 2.9:

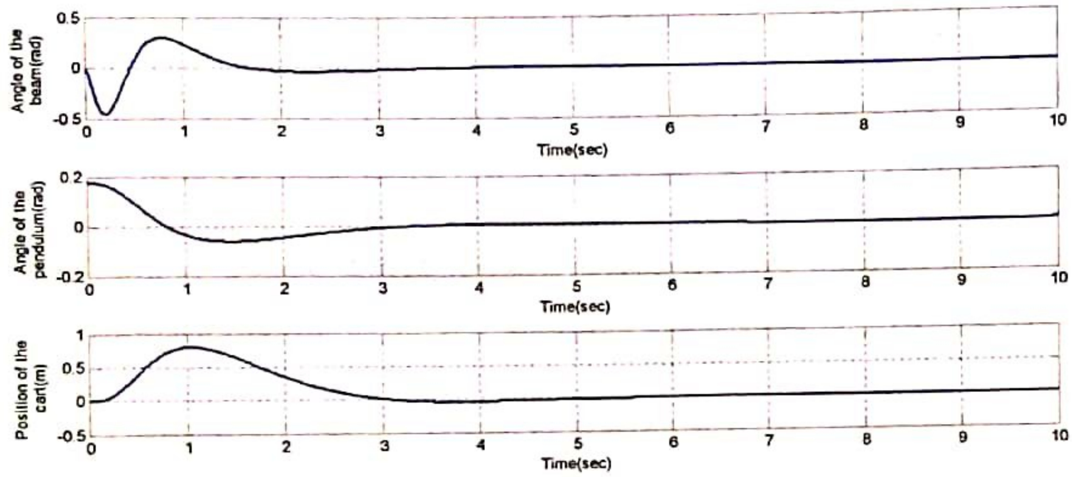


Figure 2.9 Closed loop response.

In this case the beam rotates and forces the cart and pendulum to reach zero position after about four seconds.

Case 3 assuming that all initial conditions equal zero except r =5cm and Ø=π/18, the responses are shown in the following figure

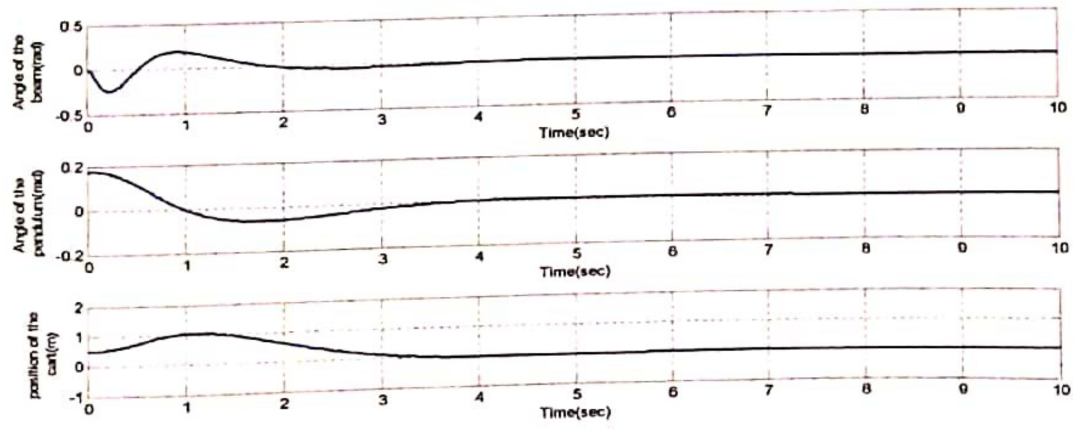


Figure 2.10 Closed loop response.

Now the beam moves and put the cart at its center and the pendulum motion is quenched in about eight seconds.

In figures 2.8, 2.9, and 2.10 we see that the controller stabilize the system and make the steady state of the beam, pendulum, and cart reach zero, doing this is the first step to design a control system for the mechanical system in this project.

Now check the internal stability using Lyapunov method which says that the system is asymptotically stable if

$$A^T P + PA < \mathbf{0}_{nxm} \tag{2-15}$$

Where P:Symmetric positive definite matrix

$$A^T P + PA = -Q \tag{2-16}$$

Where Q:Symmetric positive definite matrix.

Assume Q=eye(6)

And using MATLAB to compute P using lyap function we get

```
>> Q=eye(6)
Q =
    1   0   0   0   0   0
    0   1   0   0   0   0
    0   0   1   0   0   0
    0   0   0   1   0   0
    0   0   0   0   1   0
    0   0   0   0   0   1
```

```
>> P=lyap((A-B*K1)',Q)
P =
1.0e+003 *
   0.0149   0.0002  -0.1469  -0.1317  -0.0412  -0.0247
   0.0002   0.0000   0.0006  -0.0007  -0.0000  -0.0002
  -0.1469   0.0006   5.2945   3.2764   1.2356   0.5546
  -0.1317  -0.0007   3.2764   2.5168   0.8239   0.4277
  -0.0412  -0.0000   1.2356   0.8239   0.3000   0.1410
  -0.0247  -0.0002   0.5546   0.4277   0.1410   0.0738
>> eig(P)
ans =
  1.0e+003 *
   0.0000
   0.0003
   0.0034
   0.0090
   0.3569
   7.8306
```

As no pole of the matrix P located at the right we say that the system is asymptotically stable.

2.4 Tracking System Design

After the system is regulated and all of its states go to zero in the steady state region the position of the cart must be determined by the user taking into consideration that all other states must go to zero after a period of time, this will be done by building a tracking system.

The type of our system is zero as there is no poles at the origin in the s-plane, so the type of the tracking system that must be constructed is type one which has an integrator that increase the type number of the system by one.

The system shown in Figure (2.11) is the full tracking system

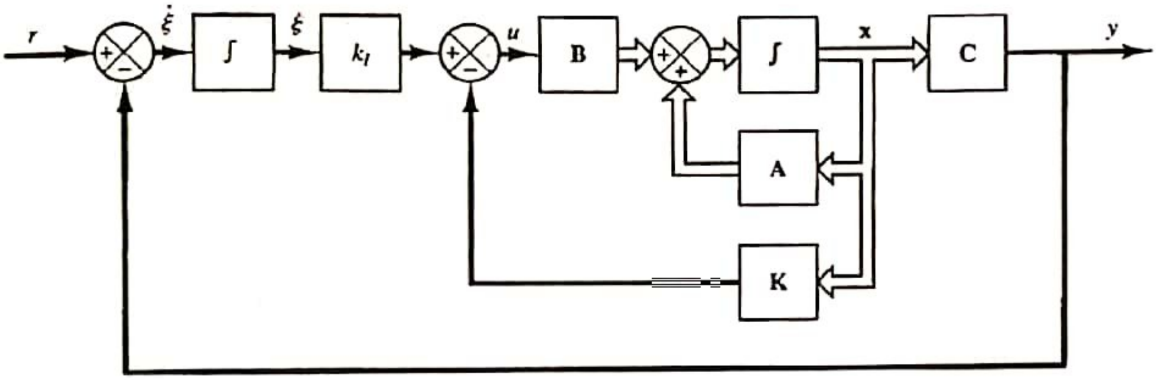


Figure 2.11 Full tracking system.

Where :

r(t) : reference input.

ξ: output of the integrator.

$$U = -Kx + K_I \xi \tag{2-17}$$

$$\dot{\xi} = r - y = r - Cx \tag{2-18}$$

Now

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\zeta} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{nxn} & \mathbf{0}_{nx1} \\ -\mathbf{C}_{1xn} & 0_{1x1} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \zeta \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{nx1} \\ 0 \end{bmatrix} U + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r \tag{2-19}$$

Our goal is to design Asymptotically stable servo system y(∞)→r(∞) and x(∞),ξ(∞), U(∞) approach constant value.

At steady state

$$\begin{bmatrix} \dot{\mathbf{x}}(\infty) \\ \dot{\zeta}(\infty) \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\mathbf{nxn}} & \mathbf{0}_{\mathbf{nx1}} \\ -\mathbf{C}_{\mathbf{1xn}} & 0_{\mathbf{1x1}} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \zeta \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{\mathbf{nx1}} \\ 0 \end{bmatrix} \mathrm{U}(\infty) + \begin{bmatrix} \mathbf{0} \\ 1 \end{bmatrix} r(\infty) \tag{2-20}$$

Subtract (2-20) from (2-19)

$$\begin{bmatrix} \dot{\mathbf{x}} - \dot{\mathbf{x}}(\infty) \\ \dot{\zeta} - \dot{\zeta}(\infty) \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\mathbf{nxn}} & \mathbf{0}_{\mathbf{nx1}} \\ -\mathbf{C}_{\mathbf{1xn}} & 0_{\mathbf{1x1}} \end{bmatrix} \begin{bmatrix} \mathbf{x} - x(\infty) \\ \zeta - \zeta(\infty) \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{\mathbf{nx1}} \\ 0 \end{bmatrix} \mathbf{U} - \mathbf{U}(\infty) + 0 \tag{2-21}$$

Now define

$\dot{\mathbf{x}} - \dot{\mathbf{x}}(\infty) = e_x(t)$

$\zeta - \zeta(\infty) = e_\zeta(t)$

$U(t) - U(\infty) = U_e(t)$

Then

$$\begin{bmatrix} \dot{e}(x) \\ \dot{e}(\zeta) \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\mathbf{nxn}} & \mathbf{0}_{\mathbf{nx1}} \\ -\mathbf{C}_{\mathbf{1xn}} & 0_{\mathbf{1x1}} \end{bmatrix} \begin{bmatrix} e_x \\ e_\zeta \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{\mathbf{nx1}} \\ 0 \end{bmatrix} \mathbf{U}_e(t)$$

$$\dot{\mathbf{e}} = \hat{\mathbf{A}}\mathbf{e} + \hat{\mathbf{B}}\mathbf{U}_e \tag{2-22}$$

Where

$$\hat{\mathbf{A}} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & 0 \end{bmatrix}$$

$$\hat{\mathbf{B}} = \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix}$$

$$U_e(t) = U(t) - U(\infty)$$
$$U_e(t) = (-Kx + K_I\zeta) - [-Kx(\infty) + K_I\zeta(\infty)]$$
$$U_e(t) = -K[x - x(\infty)] + K_I[\zeta - \zeta(\infty)]$$
$$U_e(t) = -Ke_x + K_I e_\zeta$$
$$U_e(t) = -[\mathbf{K} \;\vdots\; -K_I]\begin{bmatrix}\mathbf{e_x}\\ \mathbf{e_\zeta}\end{bmatrix} \tag{2-23}$$
$$U_e(t) = -\hat{\mathbf{K}}\begin{bmatrix}\mathbf{e_x}\\ \mathbf{e_\zeta}\end{bmatrix}$$

Where K_I is the last element.

Put equation (2-20) in (2-21)

$$\dot{\mathbf{e}} = \hat{\mathbf{A}}\mathbf{e} + \hat{\mathbf{B}}(-\hat{\mathbf{K}}\mathbf{e})$$
$$\dot{\mathbf{e}} = (\hat{\mathbf{A}} - \hat{\mathbf{B}}\hat{\mathbf{K}})\mathbf{e} \tag{2-24}$$

Equation 2-24 is the design equation of the tracking system, if the pair($\hat{\mathbf{A}}$, $\hat{\mathbf{B}}$) is controllable this means that the controllable matrix has rank equal to n+1, then pole placement method can be used to get $\hat{\mathbf{K}}$.

Using MATLAB we get the new matrices.

>> Ahat=[A zeros(6,1);-C 0];

$$\hat{\mathbf{A}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -34.868 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1.2707 & 0 & -1.2707 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ -10.1655 & 0 & 0.3555 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1.000 & 0 & 0 \end{bmatrix}$$

>> Bhat=[B;0];

$$\hat{\mathbf{B}} = \begin{bmatrix} 0 \\ 4.6041 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Now the extended controllability matrix for ($\hat{\mathbf{A}}, \hat{\mathbf{B}}$) will be

>> Coh=ctrb(Ah,Bh)

$$\mathbf{Coh} = 10^3 \begin{bmatrix} 0 & 0.0005 & 0 & 0 & 0 & 0.1632 & 0 \\ 0.0005 & 0 & 0 & 0 & 0.1632 & 0 & -0.0073 \\ 0 & 0 & 0 & 0.0006 & 0 & -0.0007 & 0 \\ 0 & 0 & 0.0006 & 0 & -0.0007 & 0 & 0.2083 \\ 0 & 0 & 0 & -0.0047 & 0 & 0.0002 & 0 \\ 0 & 0 & -0.0047 & 0 & 0.0002 & 0 & -1.6592 \\ 0 & 0 & 0 & 0 & 0.0047 & 0 & -0.0002 \end{bmatrix}$$

>> rank(Coh)

ans = 7 so the tracking system is controllable.

Now compute $\hat{\mathbf{K}}$ using place function in MATLAB assuming the same required poles used in the regulator.

>>Kh=place(Ah,Bh,P)

Kh =

$$\mathbf{K} = [0.0819 \quad 0.0066 \quad -1.4876 \quad -0.9948 \quad -0.3823 \quad -0.1769 \quad 0.1981]$$

So K_I=-0.1981

Building the previous system with MATLAB as shown in Figure 2.12, Gray is the real system, Blue is the,controller, and Green is the input.

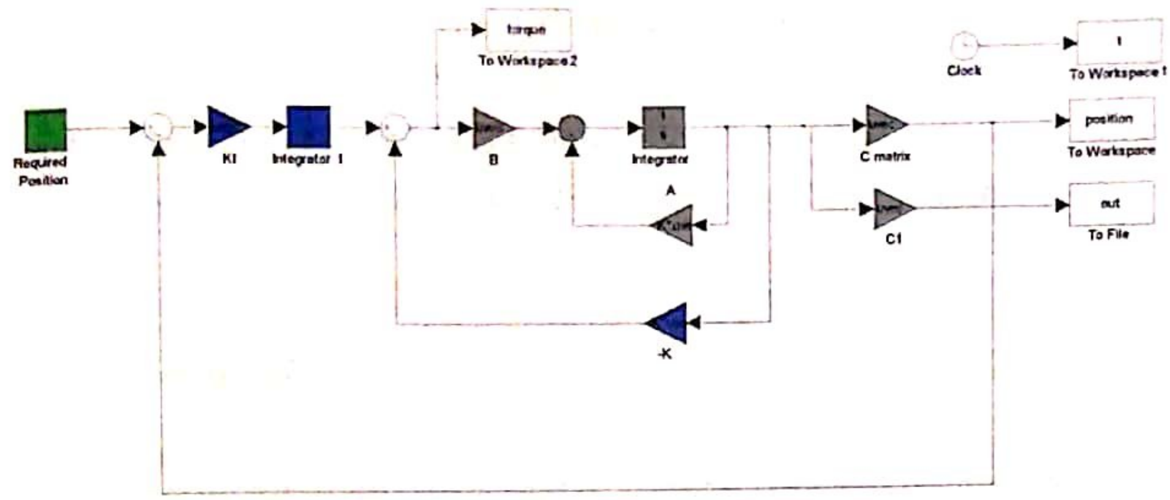


Figure 2.12 Servo Tracking system

Assume we want to position the cart at 10cm from the center of the beam we get the following response:

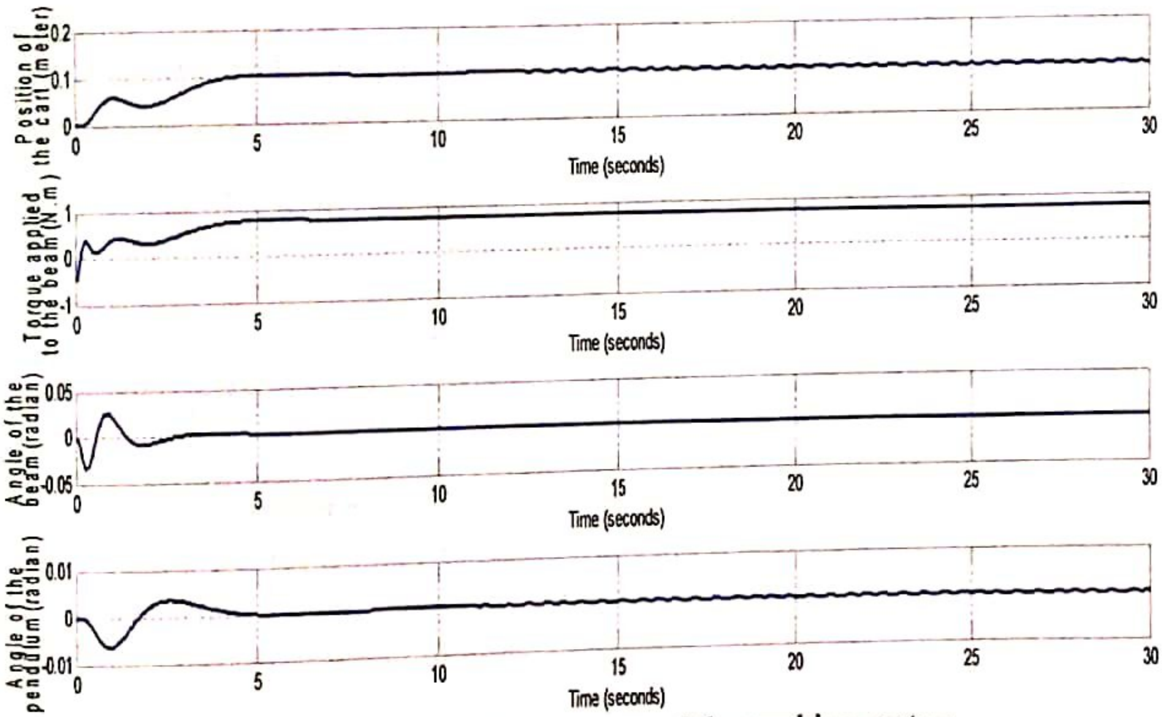


Figure 2.13 Response of the tracking system

In the previous process the tracking system managed to position the cart at 10cm away from the center of the beam, torque started to increase in the way shown in the second figure to reach finally 0.7N.m, the variation of the beam and Pendulum angles due to this process are shown in the third and forth figure respectively.

2.5 Observer Design

The six states of the system must be available in the system, in our system we have three states available $\theta, \emptyset, r$ angle of the beam, angle of the pendulum, and position of the cart respectively, the other three states can be constructed using an observer which will take the measured states from the sensors and estimate the unmeasured states using a special technique.

Before Building such an observer we must check if the system is observable or not, to do this we build a matrix which called an Observabillity matrix as follow

$$O = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix} \qquad (2\text{-}25)$$

In our system we have six states so n=6, so

$$O = \begin{bmatrix} C \\ CA \\ CA^2 \\ CA^3 \\ CA^4 \\ CA^5 \end{bmatrix}$$

$$
O = \begin{bmatrix}
1.0000 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1.0000 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1.0000 & 0 \\
0 & 1.0000 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1.0000 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1.0000 \\
0 & 0 & 0 & 0 & -34.8680 & 0 \\
1.2707 & 0 & -1.2707 & 0 & 0 & 0 \\
-10.1655 & 0 & 0.3555 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -34.8680 \\
0 & 1.2707 & 0 & -1.2707 & 0 & 0 \\
0 & -10.1655 & 0 & 0.3555 & 0 & 0 \\
354.4513 & 0 & -12.3966 & 0 & 0 & 0 \\
-1.6147 & 0 & 1.6147 & 0 & -44.3064 & 0 \\
0.4518 & 0 & -0.4518 & 0 & 354.4513 & 0 \\
0 & 354.4513 & 0 & -12.3966 & 0 & 0 \\
0 & -1.6147 & 0 & 1.6147 & 0 & -44.3064 \\
0 & 0.4518 & 0 & -0.4518 & 0 & 354.4513
\end{bmatrix}
$$

The rank of this matrix must be equal to the number of the system states, using MATLAB

\>> rank(O)

ans = 6 so the system is Observable.

For our system it is observable by only one sensor which measures the position of the cart, but for more accurate results an additional two sensors are used to measure the Beam angle and the Pendulum angle, so

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

The observer that will be used is the full Observer, the output of this Observer will be the six states of the system which includes the three measured states.

Consider the system as

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \qquad (2\text{-}26)$$
$$\mathbf{Y} = \mathbf{C}\mathbf{x}$$

Observer model

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}u + \mathbf{L}(\mathbf{y} - \hat{\mathbf{y}}) \qquad (2\text{-}27)$$

Where

$\hat{\mathbf{x}}$: Estimated states

$\mathbf{y}$: Real output.

$\hat{\mathbf{y}}$: Estimated output.

$\mathbf{L}$: Observer gain matrix, to be designed such that $\hat{\mathbf{x}} = \mathbf{x}$

Now 2-27 becomes

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}u + \mathbf{LC}(\mathbf{x} - \hat{\mathbf{x}}) \qquad (2\text{-}28)$$

Subtract 2-28 from 2-26 to get

$$\dot{x} - \dot{\hat{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u - \mathbf{A}\hat{\mathbf{x}} - \mathbf{B}u - \mathbf{LC}(\mathbf{x} - \hat{\mathbf{x}}) \qquad (2\text{-}29)$$
$$\dot{\mathbf{x}} - \dot{\hat{\mathbf{x}}} = \mathbf{A}(\mathbf{x} - \hat{\mathbf{x}}) - \mathbf{LC}(\mathbf{x} - \hat{\mathbf{x}})$$

$$\text{Let } \mathbf{x} - \hat{\mathbf{x}} = \mathbf{e} \qquad (2\text{-}30)$$

Put 2-30 in 2-29 we get

$$\dot{\mathbf{e}} = \mathbf{Ae} - \mathbf{LCe} \qquad (2\text{-}31)$$

$$\dot{\mathbf{e}} = (\mathbf{A} - \mathbf{LC})\mathbf{e} \qquad (2\text{-}32)$$

The previous equation describes the dynamic behavior of the error vector, If matrix

$(\mathbf{A}-\mathbf{LC})$ is stable matrix , the error vector will converge to zero, and $\hat{\mathbf{x}}$ will converge to $\mathbf{x}$ regardless of the initial conditions.

The complete system with observer is shown in Figure 2.14

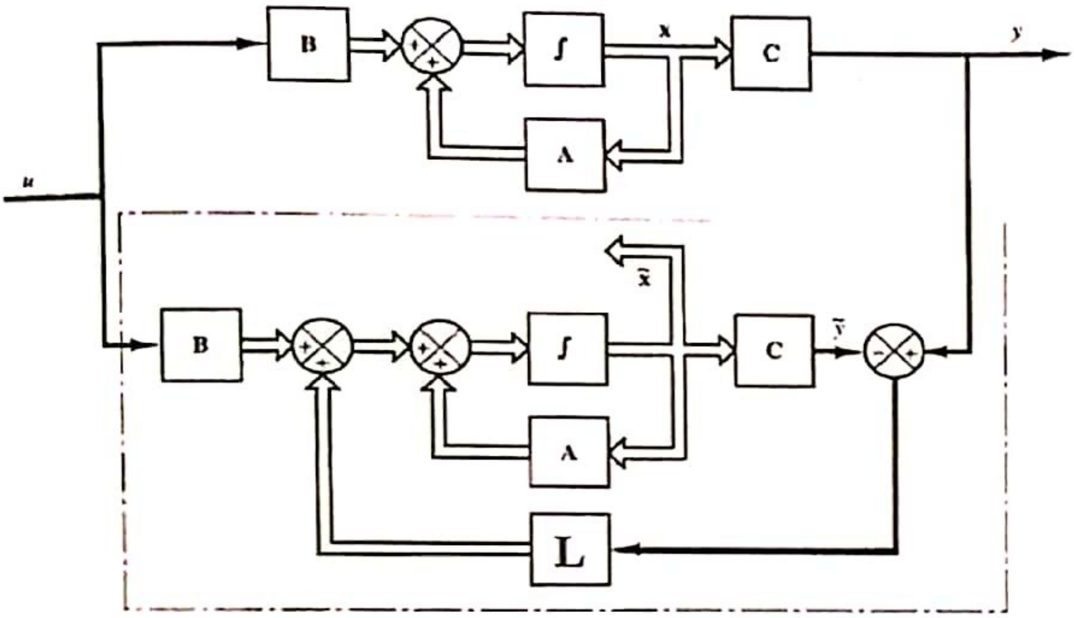


Figure 2.14 Complete system with Observer

And using MATLAB with place function we get **L** assuming the observer poles is smaller than the closed system poles.

The observer poles will be

```
>> po=P1-5

po =

  -5.2000 + 0.2000i

  -5.2000 - 0.2000i

  -5.8000

  -5.8200

  -5.8020

  -6.0000
```

And the observer matrix **L** will be

```
>> l=place(A',Cm',po)

l =

  11.3512  32.1946  -0.4103  -1.1109  -0.1408 -10.9799
  -0.2292  -1.3338  11.3577  30.9605   0.2810   1.9919
  -0.4210 -37.3082  -0.0045  -0.0252  11.1131  30.8126

>> L=l'
```

$$\mathbf{L} = \begin{bmatrix} 11.3512 & -0.2292 & -0.4210 \\ 32.1946 & -1.3338 & -37.3082 \\ -0.4103 & 11.3577 & -0.0045 \\ -1.1109 & 30.9605 & -0.0252 \\ -0.1408 & 0.2810 & 11.1131 \\ -10.9799 & 1.9919 & 30.8126 \end{bmatrix}$$ Observer matrix

Chapter Three

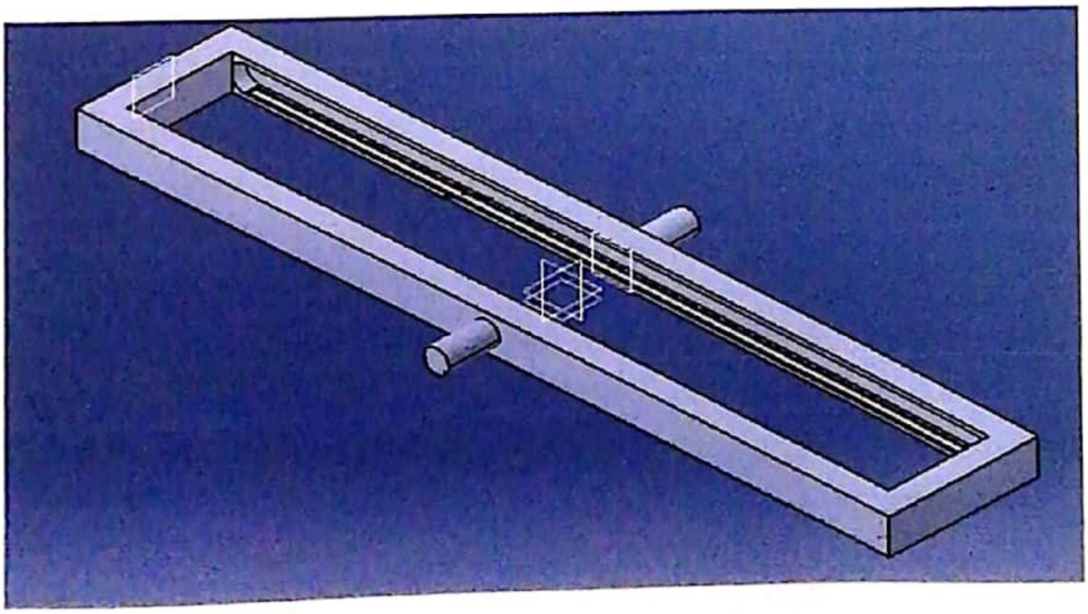
Electromechanical
Design of the system

The mechanical system should be designed using CATIA program, this design should show the whole system, and should show the mechanism that will link the motor with the beam, which is very important in the system design.

3.1 Mechanical components of the system

3.1.1 Beam

The beam shown in Figure 3.1 is used as the surface where the cart will slide on, it is supported by the stand, the beam will be controlled by the applying torque to its center, the servo motor will supply the needed torque through pulleys.



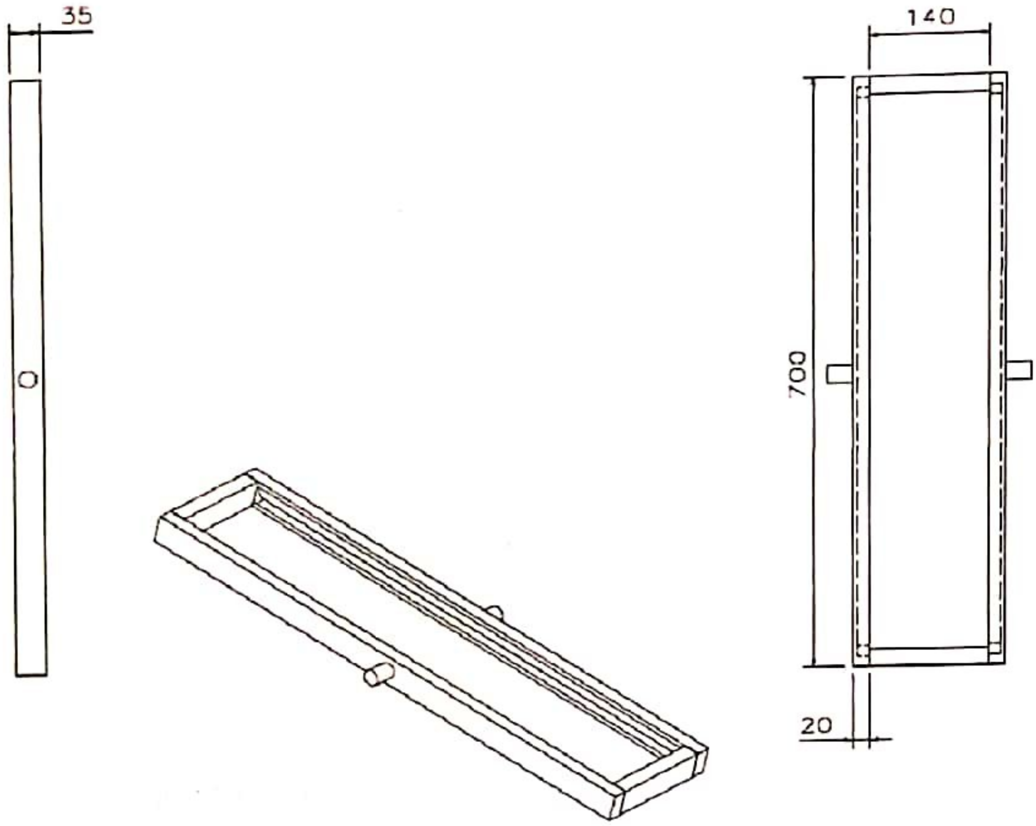
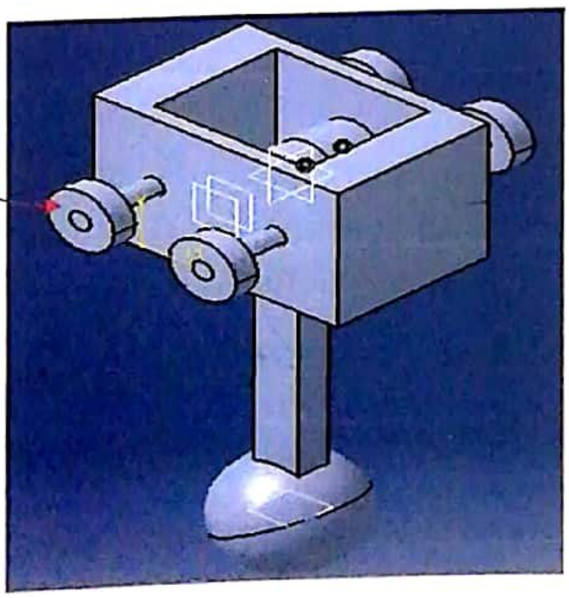


Figure 3.1 The beam (dimensions in (mm)).

3.1.2 Cart and Pendulum

The cart will slide on the beam, a pendulum will hang from it, the goal of the project is to control the movement of the cart, and to reduce the swinging angle of the pendulum, the cart will move on the beam through four bearings shown in figure 3.2 a and b.



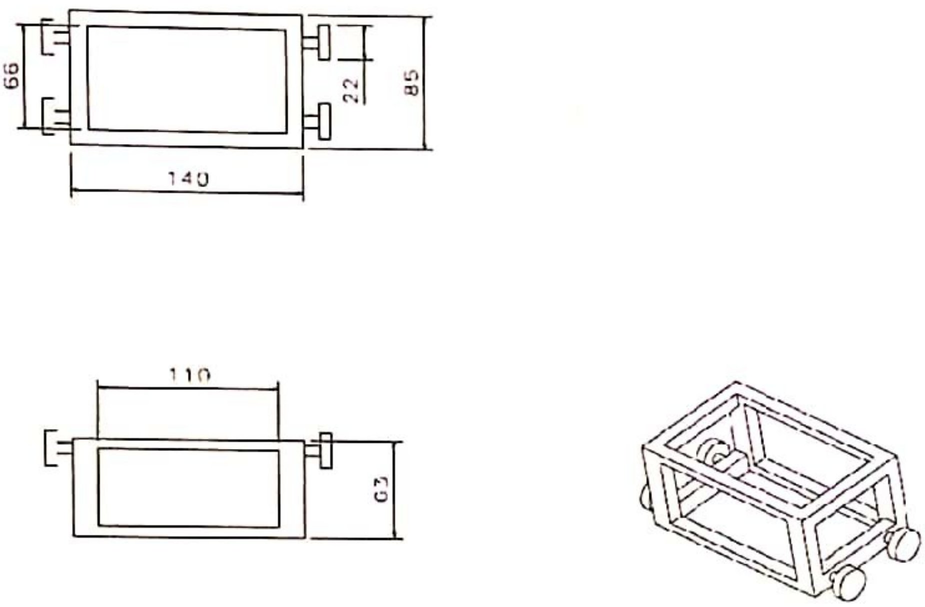


Figure 3.2a Cart and Pendulum (dimensions in (mm)).

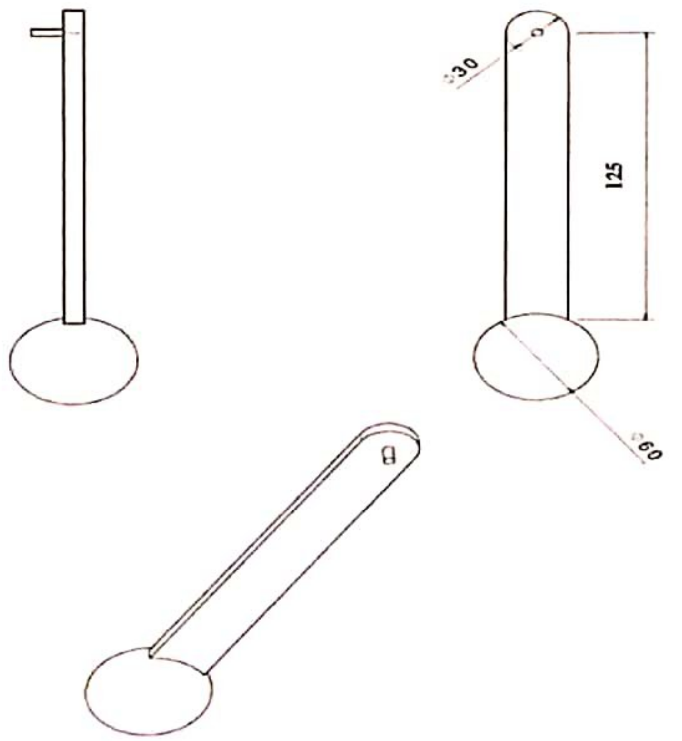


Figure 3.2b Pendulum (dimensions in (mm)).

3.1.3 Stand

The stand shown in Figure 3.3 is used to support the beam and enable it to rotate freely.

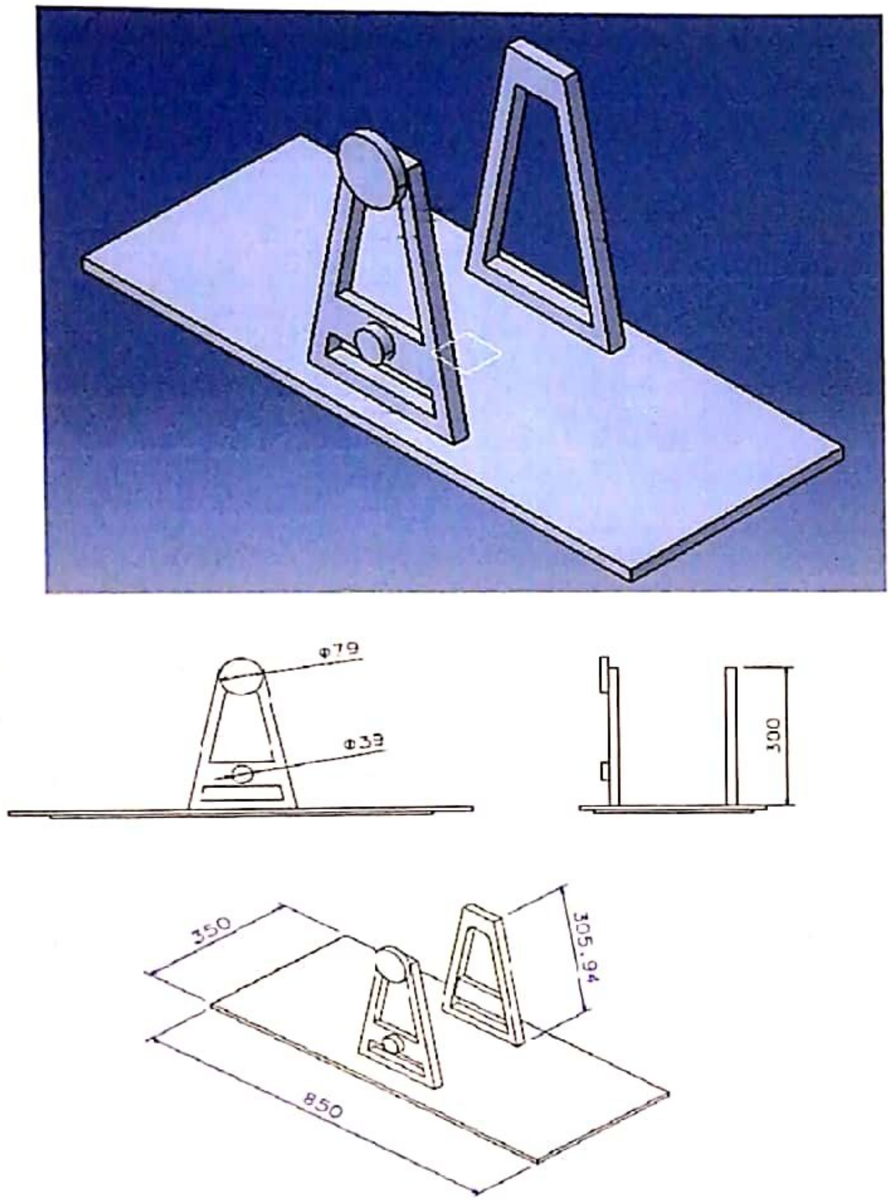


Figure 3.3 Stand (dimensions in (mm)).

3.1.4 Bearings in the system

In our system four ball bearings are used to move the cart, those bearings are chosen as small as possible as the weight of the cart is about 750g, and the external cylinder will be the moving part, so if we choose the bearings due to calculation the radius will be so small, so we chose four bearings with large factor of safety and the type is 627RS with 22mm outer diameter, 7mm internal diameter, and 7mm thickness Figure 3.4.

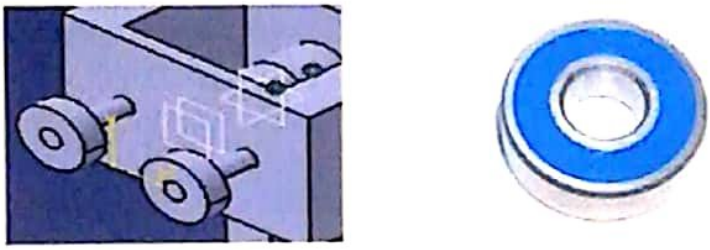


Figure 3.4 Bearings to move the cart.

Another two bearings applied to move the beam, the type of those bearings are cylindrical bearings as shown in Figure 3.5, this type of bearings can endure more stresses and weight as these bearings will be so close to the motor motion, the internal cylinder is the moving part, and the dimensions of these bearings are 27mm outer diameter, and 24mm inner diameter.

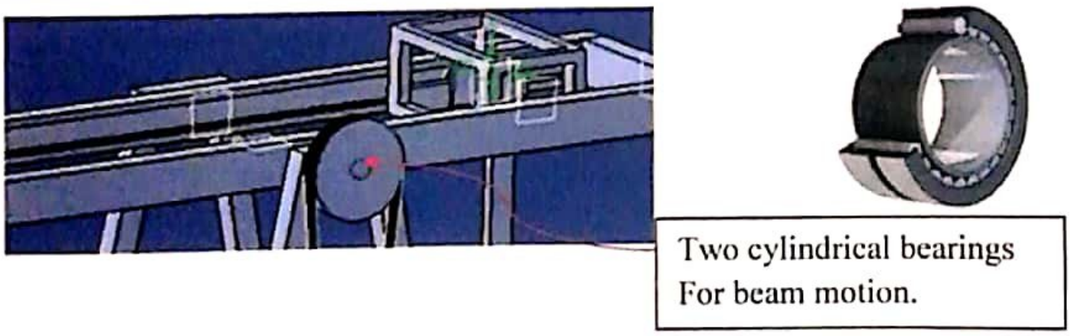


Figure 3.5 Bearings for Beam rotation.

3.1.5 Complete system

The following figure shows the complete system which contains the beam, stand, cart and pendulum, and the mechanism that is responsible for transmitting torque from the motor to the beam.

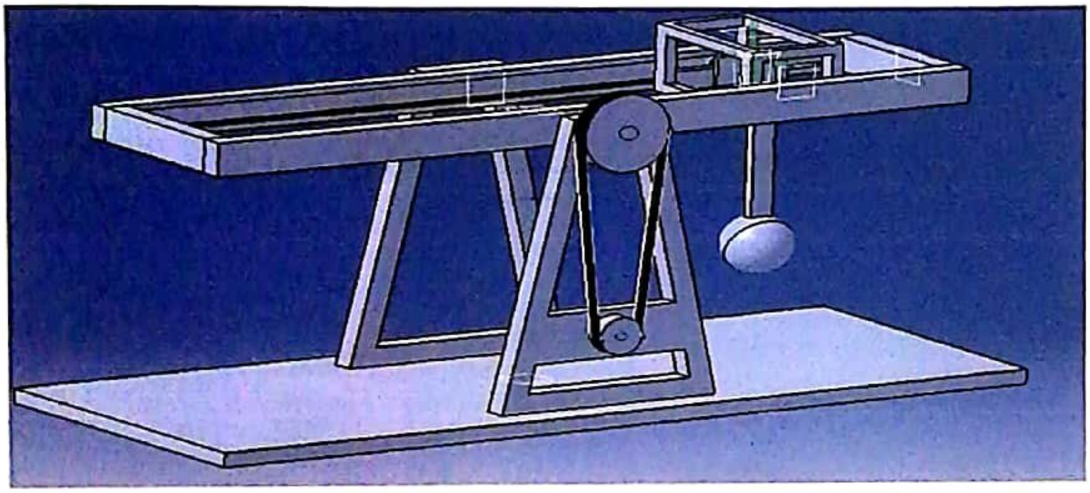


Figure 3.6 Complete system.

And the following figure shows the real system we have built with its connections:

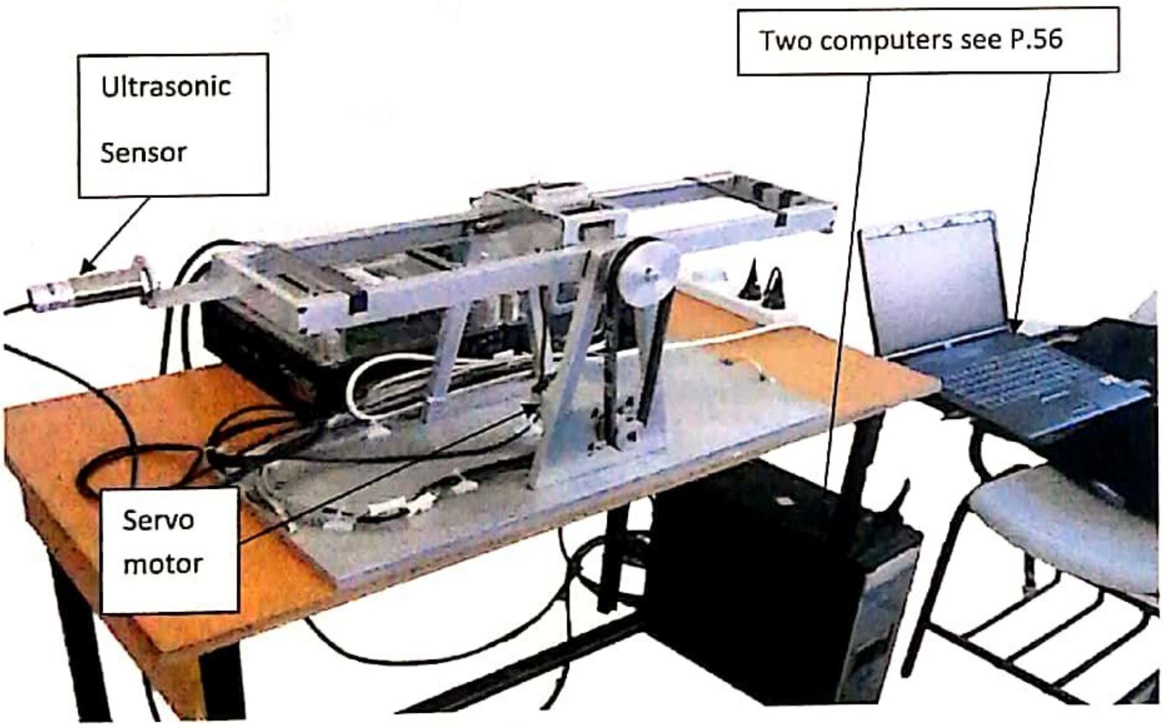


Figure 3.7 Complete Real system.

3.2 Electrical parts of the system

3.2.1 Servo motor

The servo motor with its driver shown in Figure 3.8 will supply the torque to the system through the mechanism shown, to control the angle of the beam, the type of the servo motor used is Ac 1 phase servo motor model: MSMD042P1S, Model : MBDDT2210, 3000rpm, 200Hz, B-frame will be described in chapter four. See Appendix A

Figure 3.8 Servo motor with its driver.

3.2.2 DAQ(Data Acquisition Card)

The DAQ represents the link between the system and the computer, the sensors of the system will provide feedback to the computer through the data acquisition card, the type that will be used is 6024.See appedix C

Figure 3.9 DAQ (data acquisition card).

3.2.3 Ultrasonic sensor

The Ultrasonic sensor TSPC-30S1-232 is a displacement sensor which measure distance from 10-300cm with analog voltage output 0-10 Volt proportional to the position of the cart, the sensor has good measurement rate 20 measurements/sec (can be varied), and has good resolution 4000 steps over span. See Appendix B

Figure 3.10 Ultrasonic sensor.

3.2.4 Encoder

The encoder E50S8 Figure 3.11 is 1000 pulse encoder which set to measure the angle of the Pendulum using its outputs phase A and phase B. See Appendix D

Figure 3.11 Rotary Encoder E50S8.

3.2.5 Potentiometer

The potentiometer which measures the Beam angle is frictionless, and has infinite revolutions which returns to zero every one revolution, it has three terminals two supply and one common, the output of the sensor can measure the angle of the Beam by small linear equation.

Chapter Four

Experimental tests and results

After the achievement of the theoretical part of the project with all its calculations and analysis, we have started to build the mechanical components of this project, all the components have been manufactured from Aluminum due to many reasons such as Aluminum has medium density which is smaller than that of other metals also it is solid, easy for manufacturing, and has good appearance.

The components of the project, Beam, Cart, Pendulum, and Stand are manufactured as described in the previous chapter with small modifications.

4.1 Layout of the project

The following flowchart shows how the whole project will work, the signals of the three sensors in the system will be conditioned and entered the computer through DAQ, then those signals will be processed by the controller of the system, then the system will give the required control signal to the motor that will move the system upon the user command.

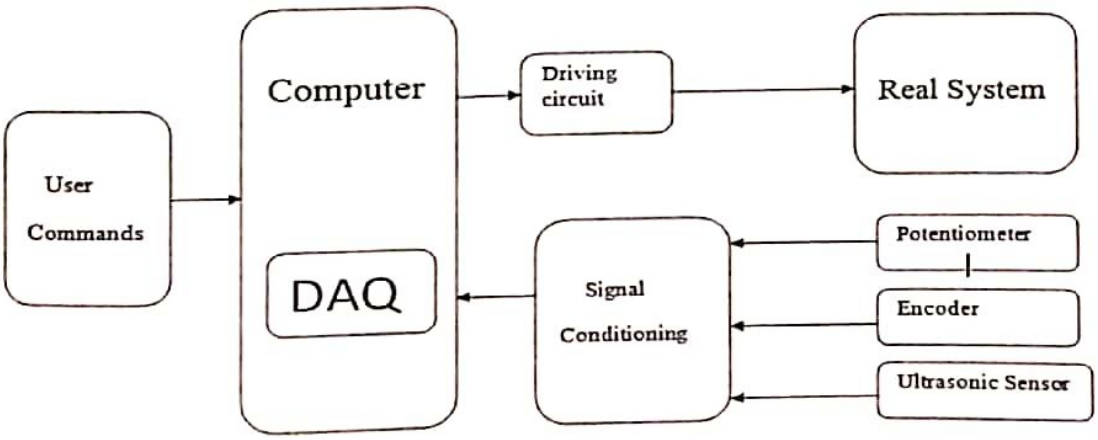


Figure 4.1 Project layout.

MATLAB is the program that was used to build and control the system using its Simulink model.

When building and controlling the project the XPC target in MATLAB was used with two separate computers Host and Target, this enable the total memory of the Host computer to be used for controlling the system, and not to be used for other operations, the Target computer which contains the DAQs accepts the signals and sends the required information to the Host via network connection.

4.2 Sensors Calibration

4.2.1 Sensors connection

After the mechanical building of the system, the three sensors ultrasonic , potentiometer, encoder which will measure Position of the cart, Beam angle, and the Pendulum angle respectively are applied to the system, then the ultrasonic and potentiometer are connected to the DAQ- 6024, analog input channel 1 for Potentiometer and analog input channel 2 for the ultrasonic sensor, the encoder is connected to Encoder Card 6602 via channel 1.

The previous three sensors are supplied by DC power supplies, the Ultrasonic sensor supplied by 24 Volt using an adaptor with 24Volt regulator, the output of the regulator is the input of the ultrasonic sensor, the Potentiometer and the encoder are supplied by one +12,-12Volt power supply, Potentiometer supplied by +5v,-5v by this power supply using two regulators one is positive LM7805 and the other one is negative LM7905, the encoder supplied by +12v from the same power supply. See appendix E.

Some of the output signals of the sensors are conditioned before entering the DAQ, the Ultrasonic sensor output is 0-10 Volt so it needs no processing before entering the DAQ, also the potentiometer output is directly connected to the DAQ as it will vary from +5Volt to -5Volt and will not exceed 10Volt, for the encoder, its

DAQ Card can accept 0-5Volt range so the outputs of the encoder phase A, and phase B are connected to two protection circuits which consist of resistor and zener 4.7Volt which works in reverse direction so if there is a pulse the circuit gives 4.7 volt and if there is no pulse the output will be zero.

The following two diagrams shows the exact connection of the sensors inputs and outputs drawn using Proteus program.

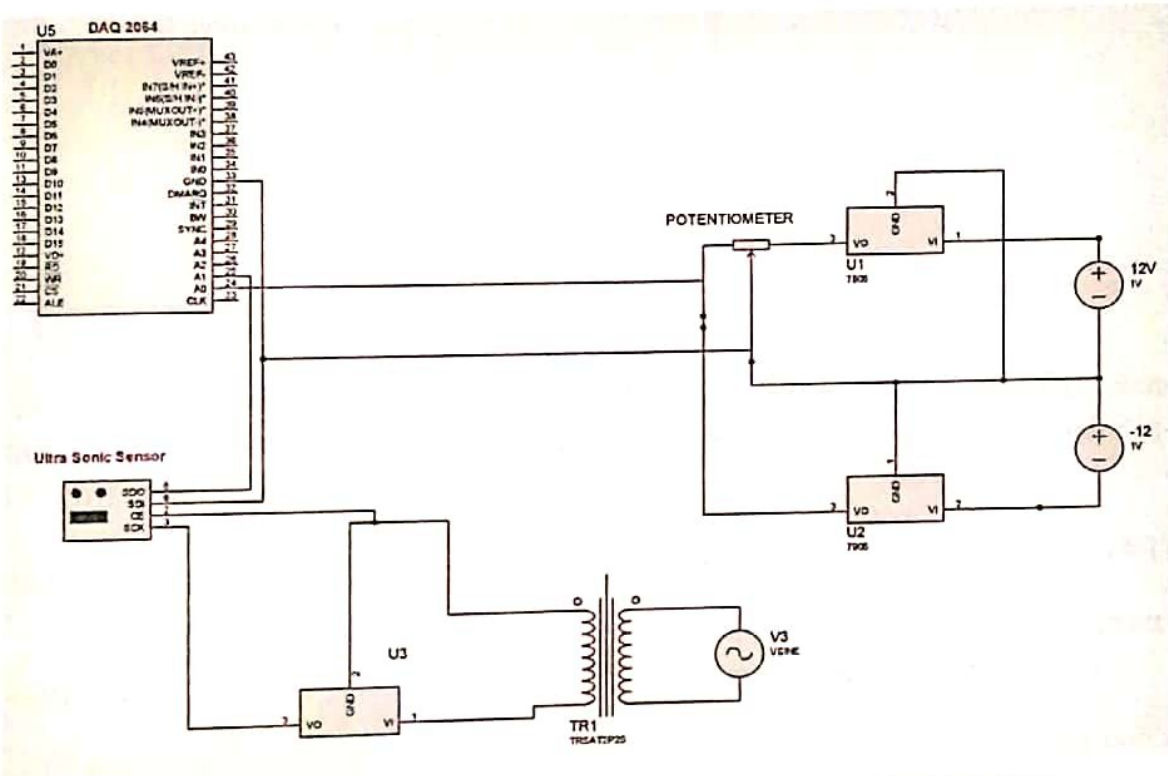


Figure 4.2 Potentiometer and Ultrasonic Connection with DAQ6024.

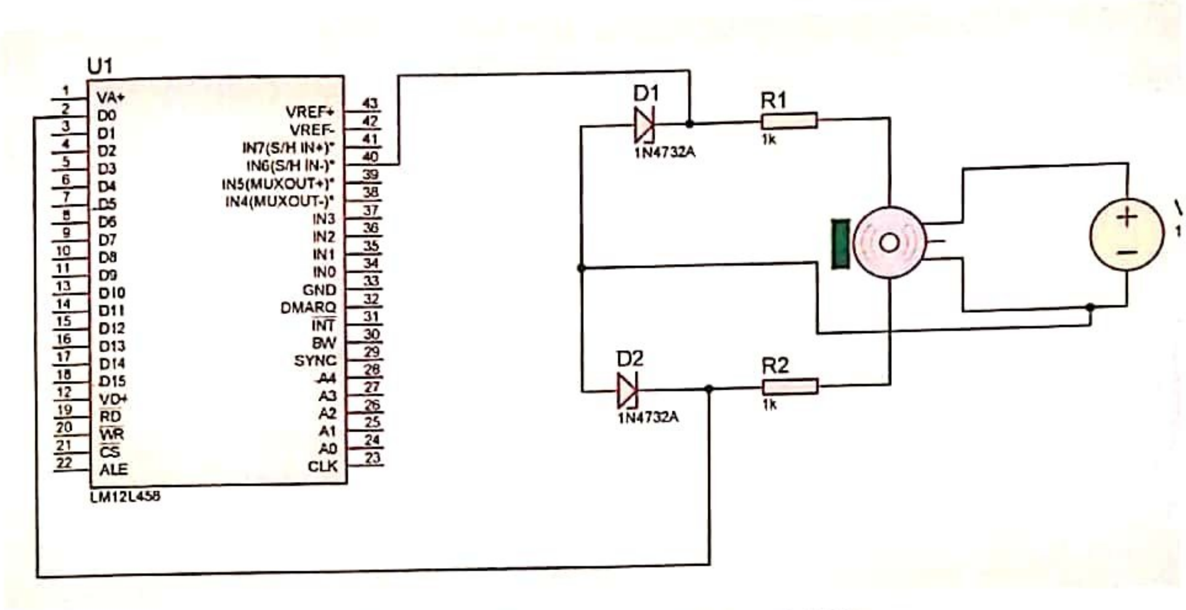


Figure 4.3 Encoder Connection with DAQ6602.

4.2.2 Potentiometer Calibration

The potentiometer calibrated as follows: at 45 degree counter wise the potentiometer output was 1.28 Volt, and at 45 counter clockwise was -1.33 Volt so the equation that relates degrees with volts is

$$\theta = 34.48V + .86 \tag{4-1}$$

This process built by MATLAB using XPC target and connected to computer using analog input channel 1 in the DAQ 6024 as shown in the following Figure

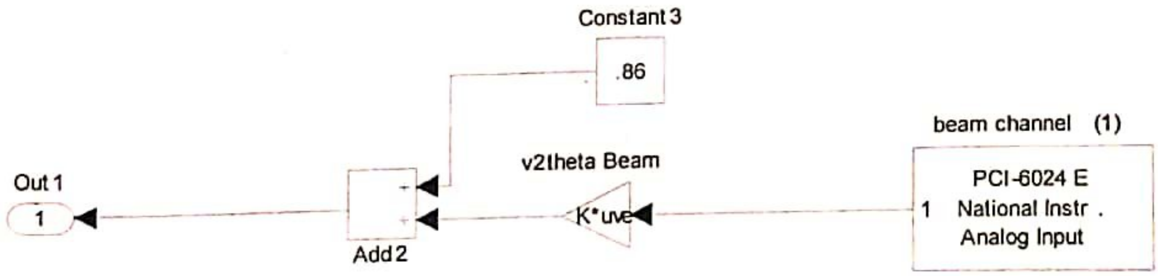


Figure 4.4 Simulink model for Potentiometer calibration.

And the response shown in Figure 4.5 resulted by moving the beam manually about 30 degrees in both directions.

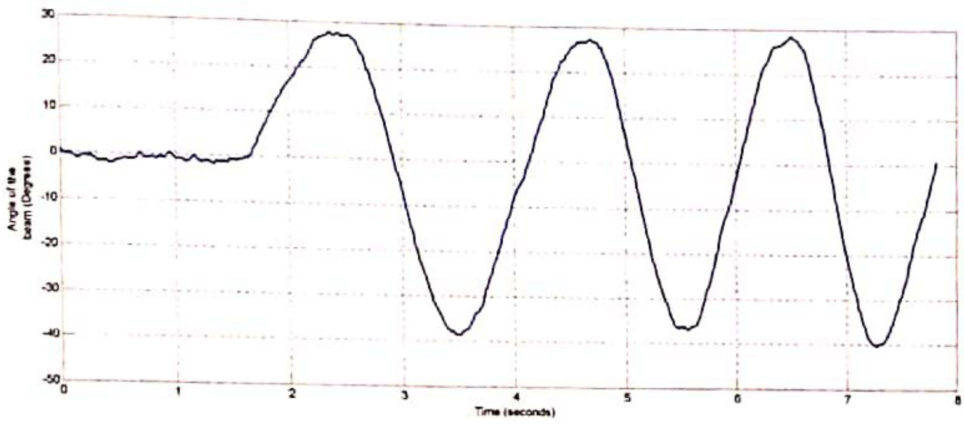


Figure 4.5 Beam movement detected by Potentiometer.

For the previous model Figure 4.4 its recommended to add gain which will convert degrees to radian when this sensor is used with the real system, also a low pass filter may be used to filter the signal if any noise appeared specially when the signal is differentiated.

4.2.3 Ultrasonic sensor calibration

The range that the cart moves in our system is 0-70cm by connecting the sensor to the SENIXVIEW software the sensor calibrated to measure from 0.1016m (Dead band) to 1m (maximum), and the output of the sensor from0-10 Volt so the equation that relates the distance to the volt is as follows:

$$\text{Distance} = 0.08984V + .1016 \tag{4-2}$$

The sensor process built by MATLAB using XPC target and connected to the computer using analog input channel 2 in the DAQ 6024 as in Figure 4.6

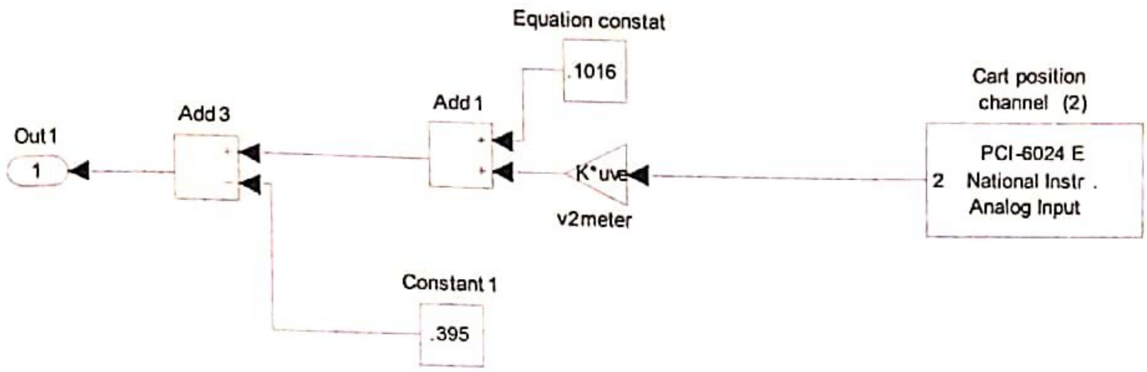


Figure 4.6 Simulink model for Ultrasonic sensor calibration.

The following figure shows the movement of the cart in both directions away from the beam

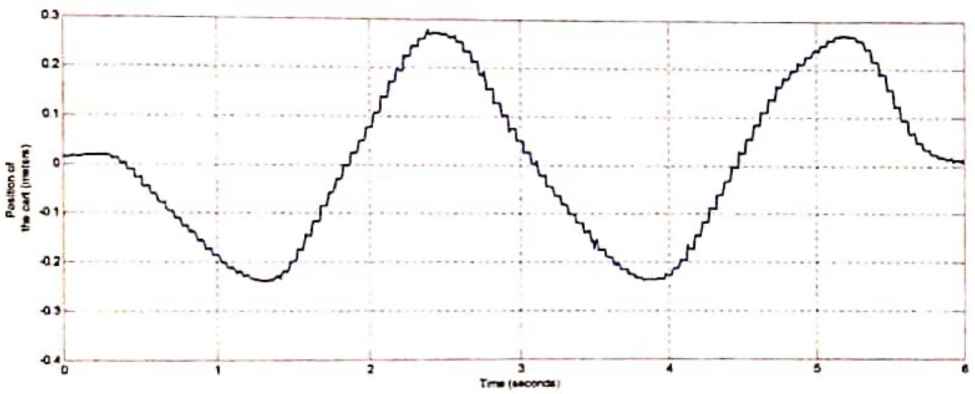


Figure 4.7 Movement of the cart.

4.2.4 Encoder calibration

The outputs of the encoder phase A-Black, and B-white are connected to the protection circuit described, then the output of the protection circuit connected to the Encoder card 6602 via channel 1 pin 2 PFI39, and pin 40 PFI40, the use of two phases is to determine the direction of rotation of the pendulum using phase shift relations.

The encoder process is built in the following figure:

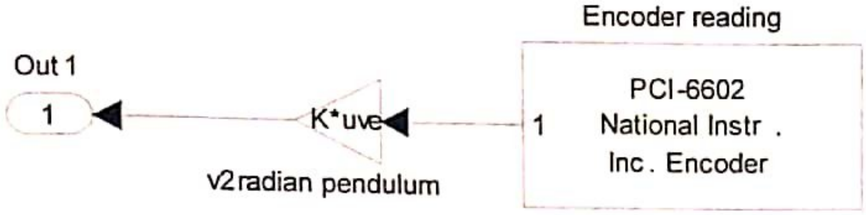


Figure 4.8 Simulink model for Encoder calibration.

The following figure shows a manually motion of the pendulum detected by the encoder.

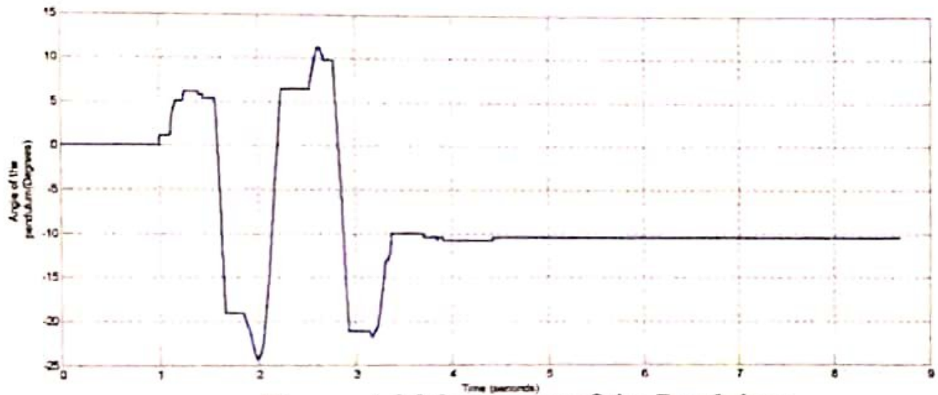


Figure 4.9 Movement of the Pendulum.

4.3 Servo motor connection and parameters setup

4.3.1 Description

After building the mathematical model for the system, we have simulated it using MATLAB, one can see that the torque needed for our system to move the cart in the range from -25cm to 25cm is about 2.5N.m, so a motor with rated torque 1.3N.m and maximum value of 3.8N.m was chosen, and two pulleys were used to double the torque, that if we need 2N.m at the beam we give 1N.m by the motor shaft.

The motor used in the project is Ac 1 phase servo motor model: MSMD042P1S, Model : MBDDT2210, 3000rpm, 200Hz, B-frame Figure 4.10

Figure 4.10 Servo motor with its Driver Model MSMD042P1S

The reason to choose servo motor is that this motor has an external complete driver that control the motor to work in several modes such a control mode which we use in the system.

The description of the servo motor Model MSMD042P1S is as follows:

MSMD	: Low inertia 200W-750W
04	: Rated output 400W
2	: 200Volt
P	: Incremental encoder with resolution 10000
1	: Design order
S	: With shaft and without oil seal

4.3.2 Connection and parameter setup

The motor connected to its driver as shown in the following figure:

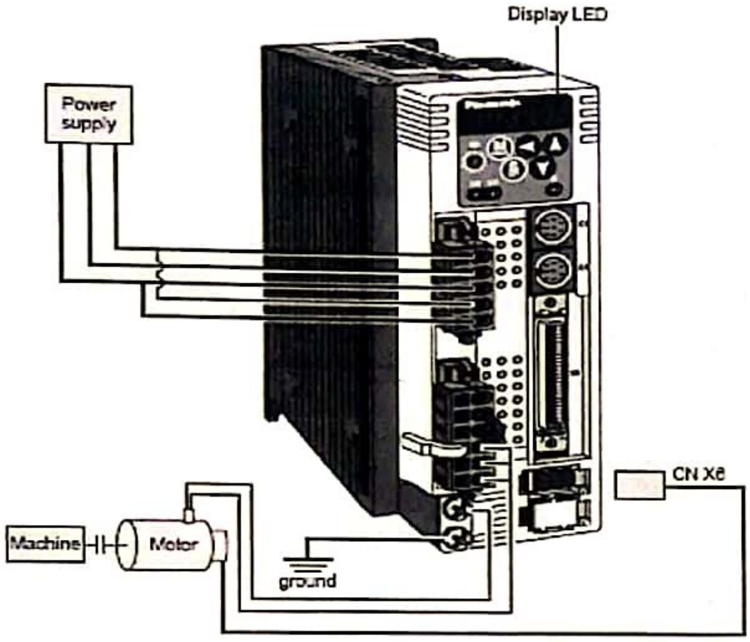


Figure 4.11 Motor connection with its Driver.

Now the control signals and supply connection are shown in figure 4.12, note that not all pins are used in our system, the used pins are:

Pin14, Pin15→connected to DAQ Analog output0, pin 22, and pin 55 respectively, this is the torque command input from the DAQ to the motor.

Pin7, Pin 41 connected to 12Volt supply, GND respectively.

Pin8 CW limit switch connected to the limit switch and the second terminal of the limit switch connected to Pin 41

Pin9 CCW limit switch connected to the limit switch and the second terminal of the limit switch connected to Pin 41

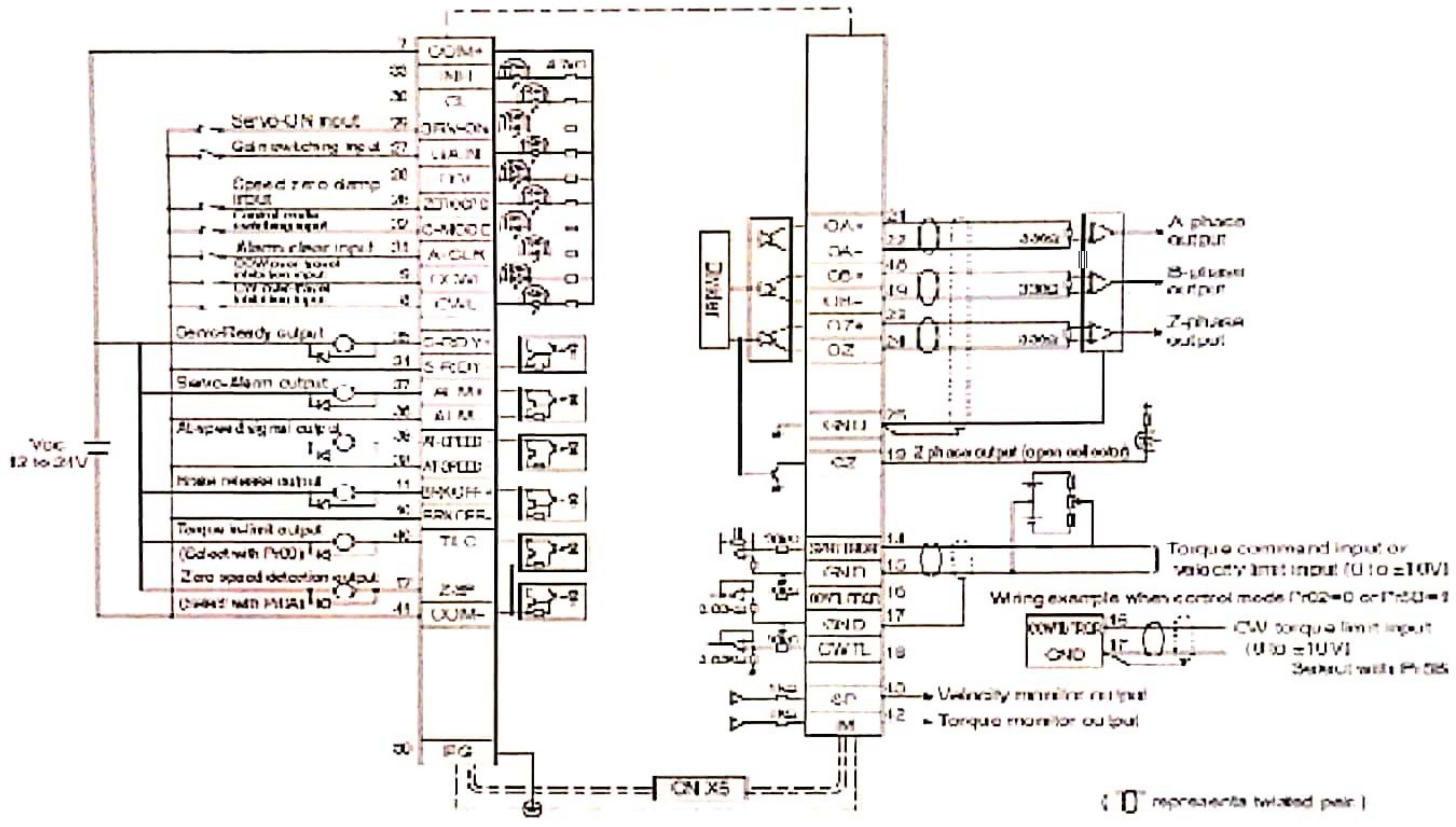


Figure 4.12 Servo motor connections.

Parameters setup

The modes of the servo motor are determined by entering certain parameters to its driver, the operating mode that was chosen for this project is torque mode Pr02-1, setup of over travel inhibit input Pr04-1, and the direction of rotation.

4.4 System test

The strategy that has been followed to work the project after the completion of its manufacturing was first to control the beam alone without the cart and without the pendulum in this step the beam is put at a desired angle, the second step was to control the beam with the cart without the pendulum, here the output is to position the cart at a specified location at the beam, finally to work the complete system Beam, Cart and Pendulum.

4.4.1 Beam Control

For the first step the transfer function of the subsystem has been derived as the following taking into consideration that the input of the subsystem will be torque and the output will be the angle of the beam,

$$Torque\ required = I\ddot{\theta} \tag{4-1}$$

Converting the previous equation to Laplace domain

$$U = Is^2\theta \tag{4-2}$$

The $Torque\ required = 2 * Torque\ of\ the\ motor$ this due to the pulleys that duplicate the torque.

So the transfer function of the system will be

$$\frac{\theta}{U_m} = \frac{2}{Is} \tag{4-3}$$

This is a system with two poles at origin the root locus of this system plotted by MATLAB with function rlocus(numerator,denominator) Figure 4.13, the response will be oscillatory.

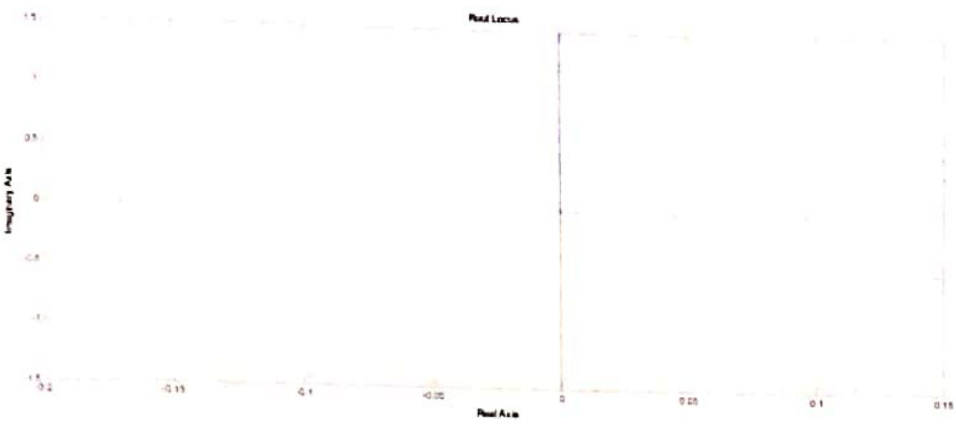


Figure 4.13 Root locus of the uncontrolled beam system.

So PD controller has to be designed to add one zero to the system making it asymptotically stable, the following shows the complete design of the controller assuming that the required settling time is four seconds and the damping ratio is 0.8.

The transfer function of the PD controller is

$$Gc = K_p + K_d s = K_p\left(s + \frac{K_p}{K_d}\right) = K_p(s + a) \quad (4\text{-}4)$$

So the characteristic equation will be

$$q(s) = 1 + \frac{K(s+a)}{0.2127s^2} \quad (4\text{-}5)$$

- The required dominant closed loop poles are $1 \pm 0.75i$.
- The phase contribution required is as the following

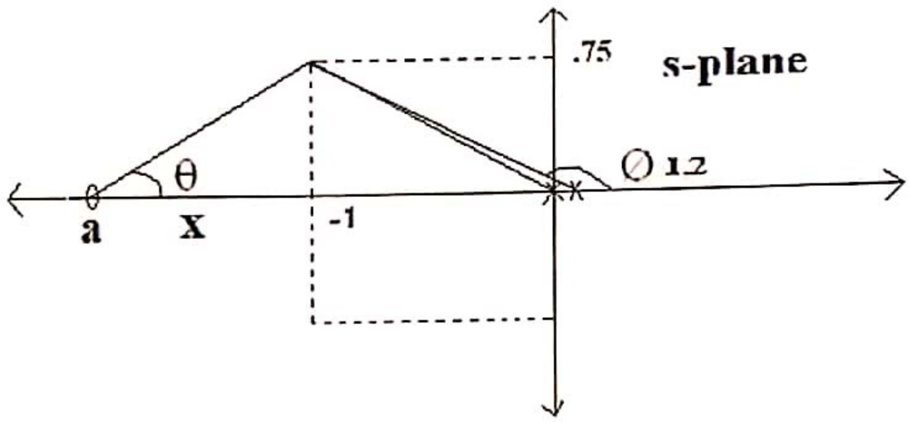


Figure 4.14 Phase contribution for PD controller.

Now the required phase contribution θ will be

$$\theta - \emptyset_1 - \emptyset_2 = r180$$

$$\emptyset_1 = \emptyset_2 = \left(180 - tan^{-1}\frac{0.75}{1}\right) = 127$$

$$\theta = -180 + 254 = 74$$

But

$$\tan 74 = \frac{0.75}{x} \rightarrow x = 0.2$$

So

$$a = \frac{K_p}{K_d} = 1.2$$

Now from (4-5)

$$\frac{1}{K} = \frac{|s + 1.2|}{|.22s||.22s|} = \frac{0.77}{1.25 * 1.25}$$

$$K = K_p = 2.03$$

$$K_d = \frac{K_p}{1.2} = 1.7$$

The resulted PD controller will be

$$Gc(s) = 2.03\left(s + \frac{2.03}{1.7}\right) = 2.03(s + 1.2) \quad (4\text{-}6)$$

The controlled system will be

$$G(s) = \frac{2.03(s+1.2)}{.22s^2} \quad (4\text{-}7)$$

Plotting the root locus again by MATLAB using function rlocus we get

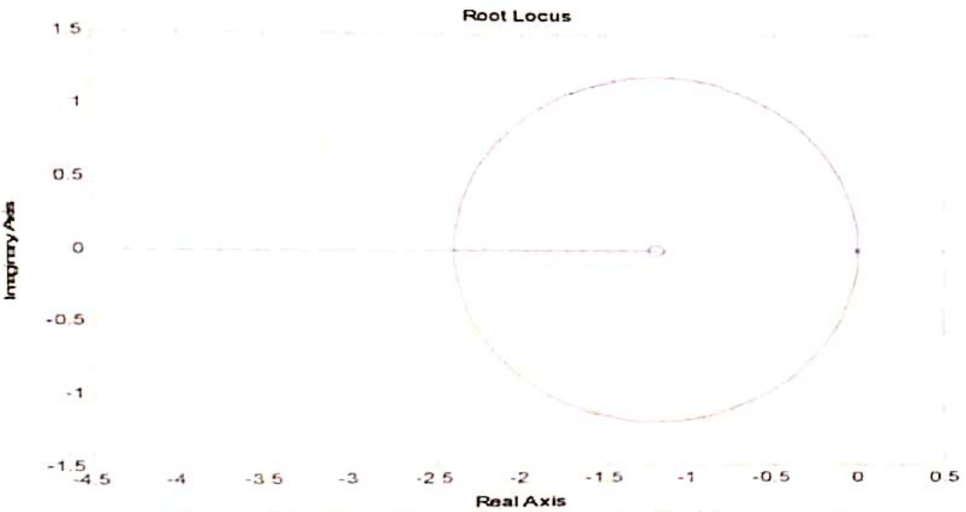


Figure 4.15 Root locus for the controlled beam system.

Building the complete system with MATLAB as in Figure 4.16, Blue section is the controller, green is the input, and the light blue are correction gains.

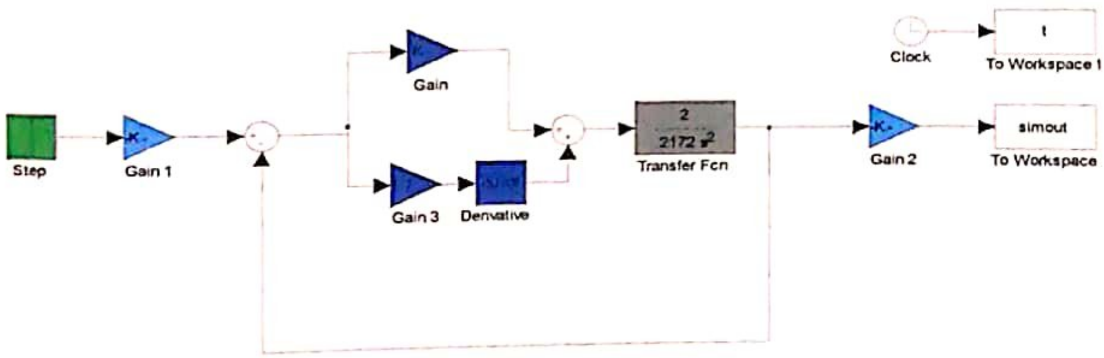


Figure 4.16 Simulink model of the controlled Beam system.

We have the following response assuming that we want to put the beam at 15 degree

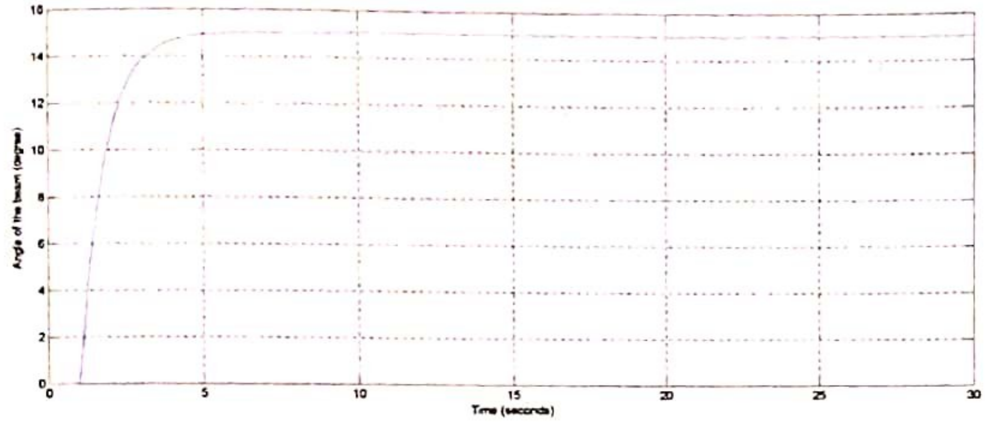


Figure 4.17 Response of the beam angle.

When the previous controller was applied to the real system the response appears to have an error, this error was caused as the system has friction which is not computed in our analysis, so the real system may be not type two which has zero error due to step input as in the theoritical one, so it needs an I element to reduce this error, an I element was added to the controller and the system works with very small error, Figure 4.18 shows the real connection of the system.

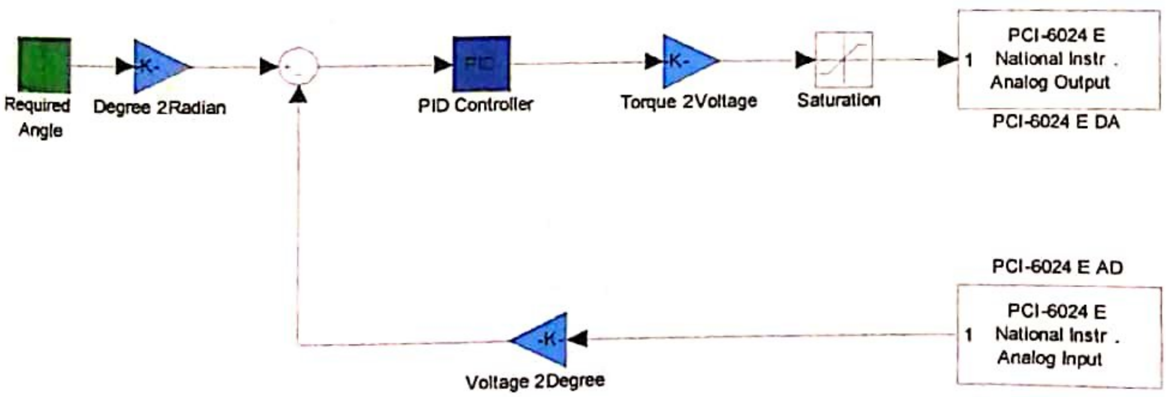


Figure 4.18 Beam system with PID controller.

4.4.2 Beam and Cart Control

The second step that has been done in the project is to controll the Beam and the cart without the pendulum the model of this system is already derived in equations (1-32), (1-33), (1-34) taking into consideration that the pendulum does not exist so the new system can be described in the following two equations

$$\ddot{\theta} I_b + m_1 g \Delta r = \Delta U \qquad (4\text{-}7)$$

$$\Delta \ddot{r} m_1 + m_1 g \theta = 0 \qquad (4\text{-}8)$$

The previous equations converted to state space model

$$\dot{x} = Ax + Bu \qquad (4\text{-}9)$$

$$y = Cx + Du \qquad (4\text{-}10)$$

Where x: The states of the system (4x1).

A: System matrix (4x4).

B : Input matrix (4x1).

C: Output matrix (1x4)

D: Feed forward matrix.

Y: Output

Now the states of the system are assumed as follow:

$$x_1 = \theta$$

$$x_2 = \dot{\theta} \qquad (4\text{-}11)$$

$$x_3 = r$$

$$x_4 = \dot{r} \qquad (4\text{-}12)$$

From (4-11), and(4-12) we have

$$\dot{x}_1 = x_2 \qquad (4\text{-}13)$$

$$\dot{x}_3 = x_4 \qquad (4\text{-}14)$$

Now the complete state space model for the subsystem will be as the following

$$\mathbf{X} = \begin{bmatrix} \theta \\ \dot{\theta} \\ r \\ \dot{r} \end{bmatrix} \qquad \dot{\mathbf{X}} = \begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ \dot{r} \\ \ddot{r} \end{bmatrix}$$

The system matrix will be

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \dfrac{-ml*g}{I} & 0 \\ 0 & 0 & 0 & 1 \\ -g & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -33.2202 & 0 \\ 0 & 0 & 0 & 1 \\ -9.8100 & 0 & 0 & 0 \end{bmatrix}$$

The input matrix is

$$\mathbf{B} = \begin{bmatrix} 0 \\ \dfrac{1}{I} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 4.5455 \\ 0 \\ 0 \end{bmatrix}$$

And the output matrix

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

Feed forward matrix is

$$\boldsymbol{D} = [0]$$

The previous subsystem is open loop unstable after checking controllability. state feedback controller was used to control this system with the following K matrix:

>> C0=ctrb(Ah,Bh)

$$CO = 10^3 \begin{bmatrix} 0 & 0.1 & 0 & 0 & 0 \\ 0.01 & 0 & 0 & 0 & 6.2553 \\ 0 & 0 & 0 & -0.0981 & 0 \\ 0 & 0 & -0.0981 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0981 \end{bmatrix}$$

>> cn=rank(C0)

cn = 5 so the system is controllable

This equals the number of the states plus one as the tracking system is included in cotrollability check.

>> Kh=place(Ah,Bh, [-2.5+2.5i,-2.5-2.5i,-1.5,-2.5,-3])

Kh = 6.3250 1.2000 -8.9568 -1.8094 1.4335

The fifth element in Kh matrix –KI is the tracking gain as discussed before in chapter two.

Building the previous system with MATLAB as in Figure 4.19, Blue section is the controller, green is the input, and the Gray is the real system.

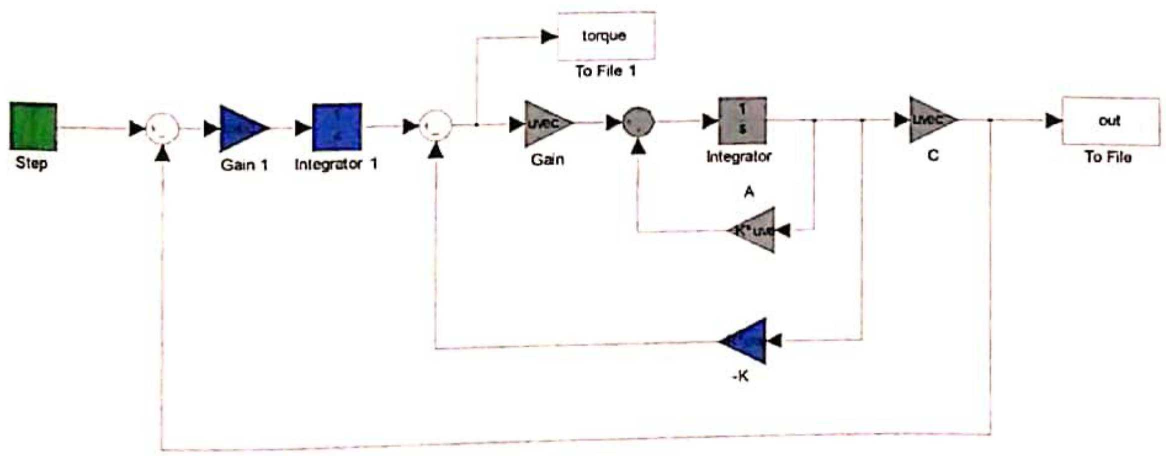


Figure 4.19 Simulink of the Beam, Cart system.

We get the following result assuming that we want to put the cart at 10cm location.

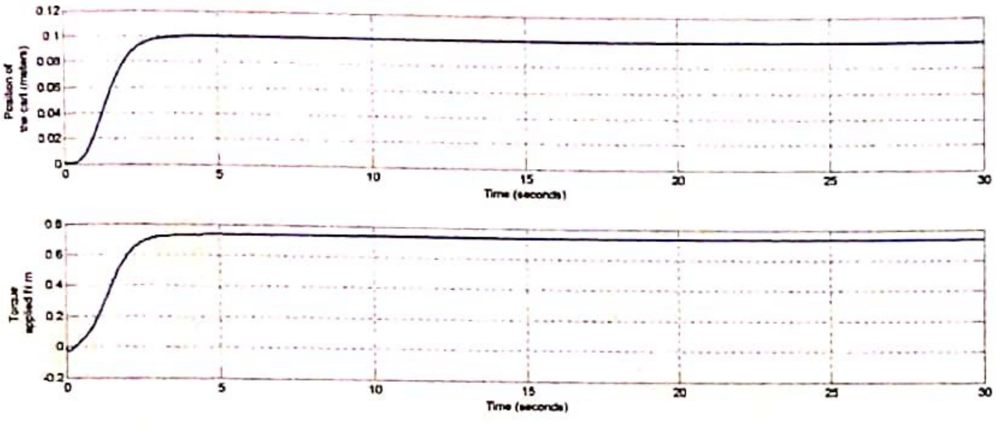


Figure 4.20 Response of 10cm tracking.

The cart positioned at 10cm after about three seconds with finalsstaedy state torque 0.7N.m

As we see the theoritical system is completely controlled and we get the required position.

For the real system we have faced some of the problems such that the four states that must be available to work the system, this was done by two ways, first taking the signals from the two sensors Potentiometer which measures the angle of the beam, and the Ultrasonic sensor which measures the position of the cart, those two signals are diffrentiated to get the velocity of these signals, in this way the four states are available.

The following Figure shows the real system with the two signals differentiated, Blue section is the controller, green is the input, orange is filter, light blue is gain and the Yellow section is the sensors input.

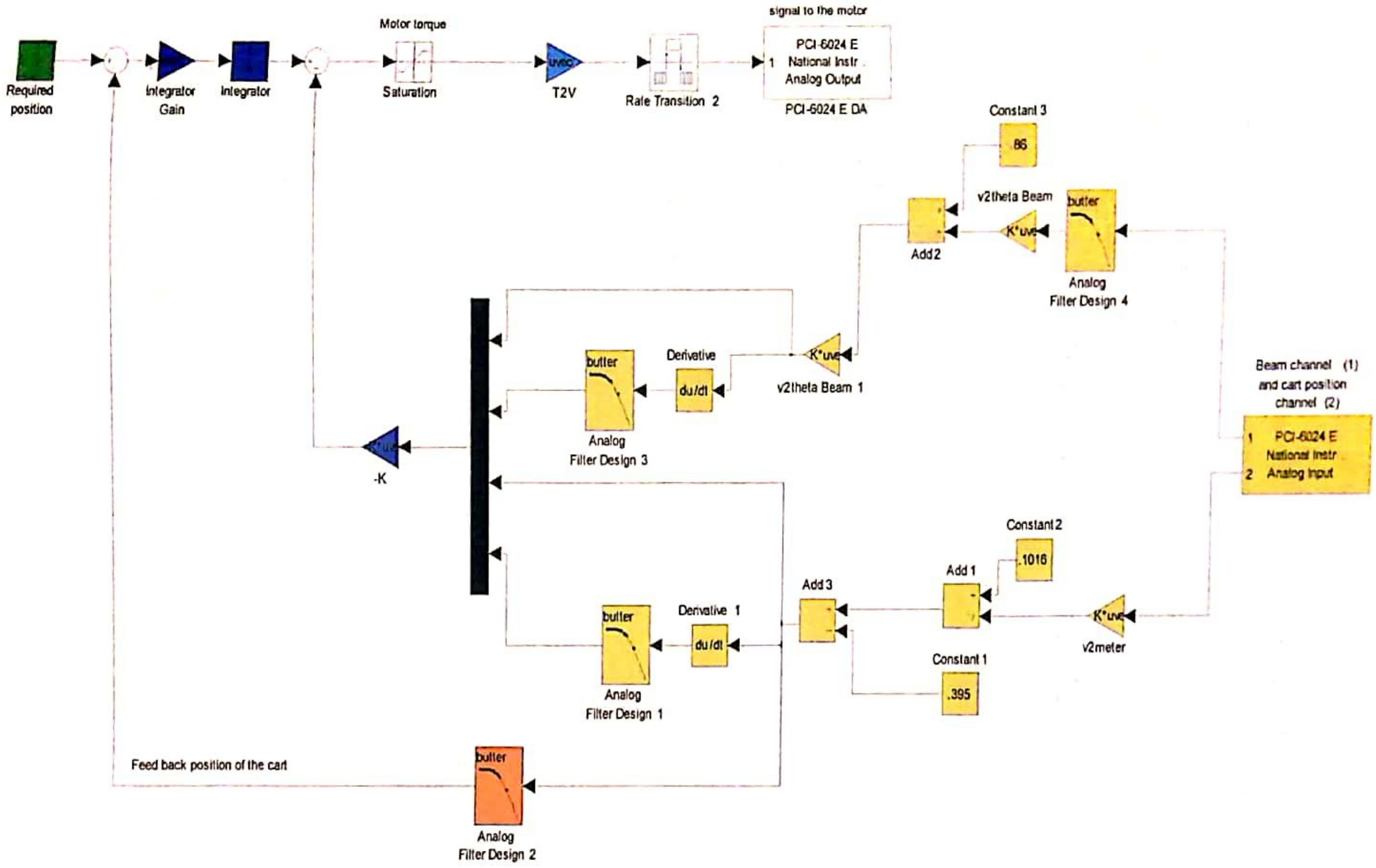


Figure 4.21 Real Beam Cart system.

The following figures show some of the trials of the Beam cart system

- Operating the system as regulator with initial condition of the cart 22cm, one can see that the cart returned to the beam center after six seconds as shown in Figure 4.22, the torque applied to do this operation is shown in Figure 4.23, and the beam movment due to this torque is shown in Figure 4.24, visit the following link to see the video for this process

http://www.youtube.com/watch?v=mhslzzOJMPk

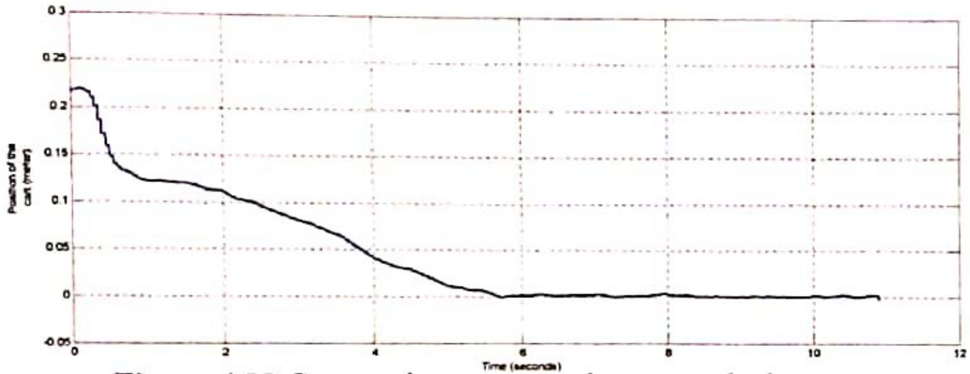


Figure 4.22 Cart motion to return the cart to the beam center.

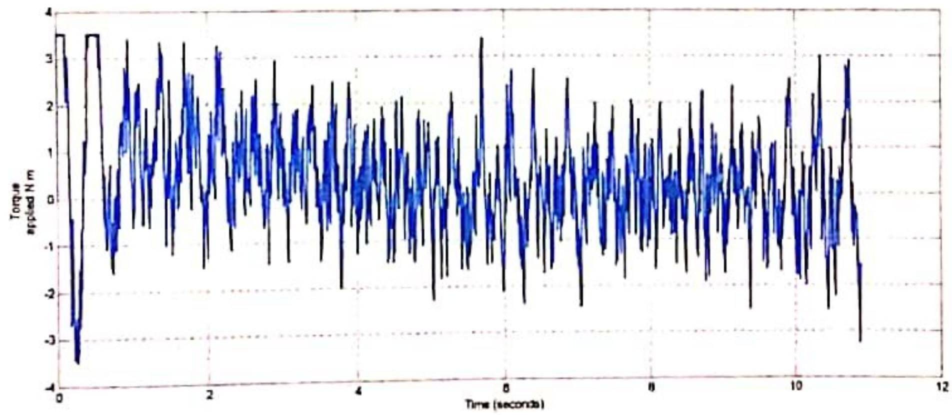


Figure 4.23 Torque applied to return the cart to the beam center.

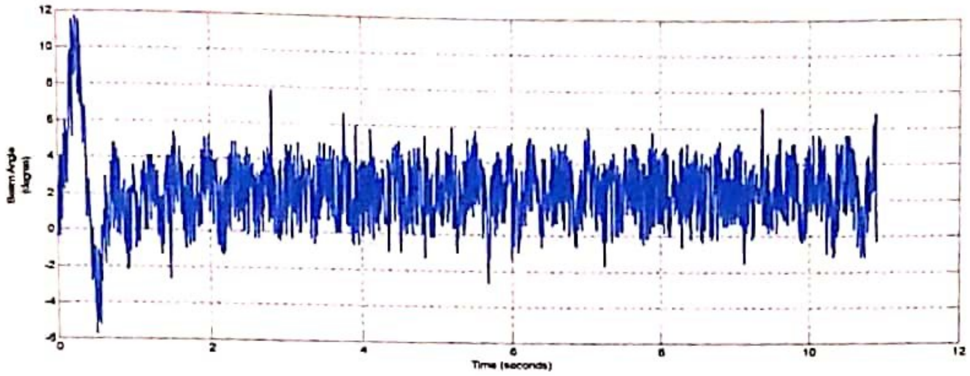


Figure 4.24 Beam movement to return the cart to the beam center.

• Now operating subsystem as tracking system to position the cart at 20 cm to the left of the beam center, we see that the cart arrived the required position after about sixteen seconds with acceptable over shoot as shown in Figure 4.25, the torque required to do this process shown in Figure 4.26, and the beam movment shown in Figure 4.27, visit the following link to see the video of the previous process:

http://www.youtube.com/watch?v=Td_reTmPo08

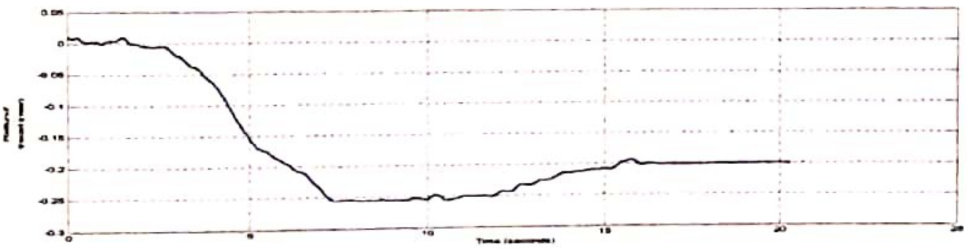


Figure 4.25 Cart motion to arrive 20cm.

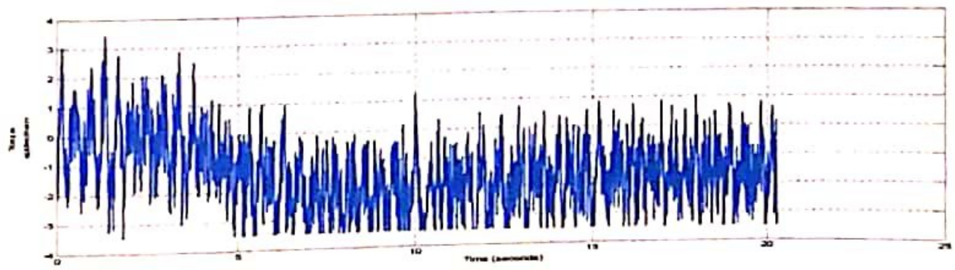


Figure 4.26 Torque applied to force the cart to reach 20cm.

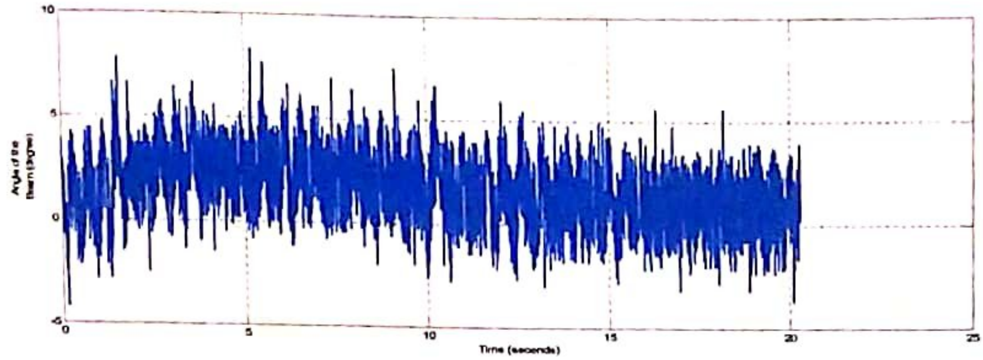


Figure 4.27 Beam movement to force the cart to reach 20cm.

The reason that make the torque and beam angle signals apears as in the previous figures, is that the motor motion and the beam response is so fast with small magnitude, and the time division in those figures are quitly large, so it apears like noisy signal, if we reduce the time division as shown in Figure 4.28 we see that it is a normal signal but it is too fast and the magnitude change is so small.

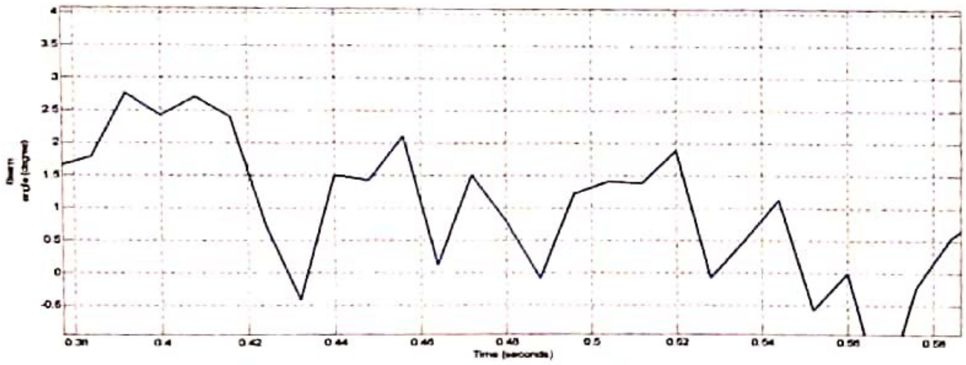


Figure 4.28 Zoom in to the Beam movement.

The second way that has been followed to get the four states was building an observer, we have checked the system if it is observable by the sensors available, and the result was that it is observable by only the ultrasonic sensor which measures the cart position but we really use the two sensors in the observer to get more accurate states, so the observer wasbuilt as shown in Figure 4.29, red section is the observer, but we have faced many problems to work the subsystem using the observer, this was caused by the real system being not as the theoritical one, some differences appeared due to friction and nonlinearities of the real system.

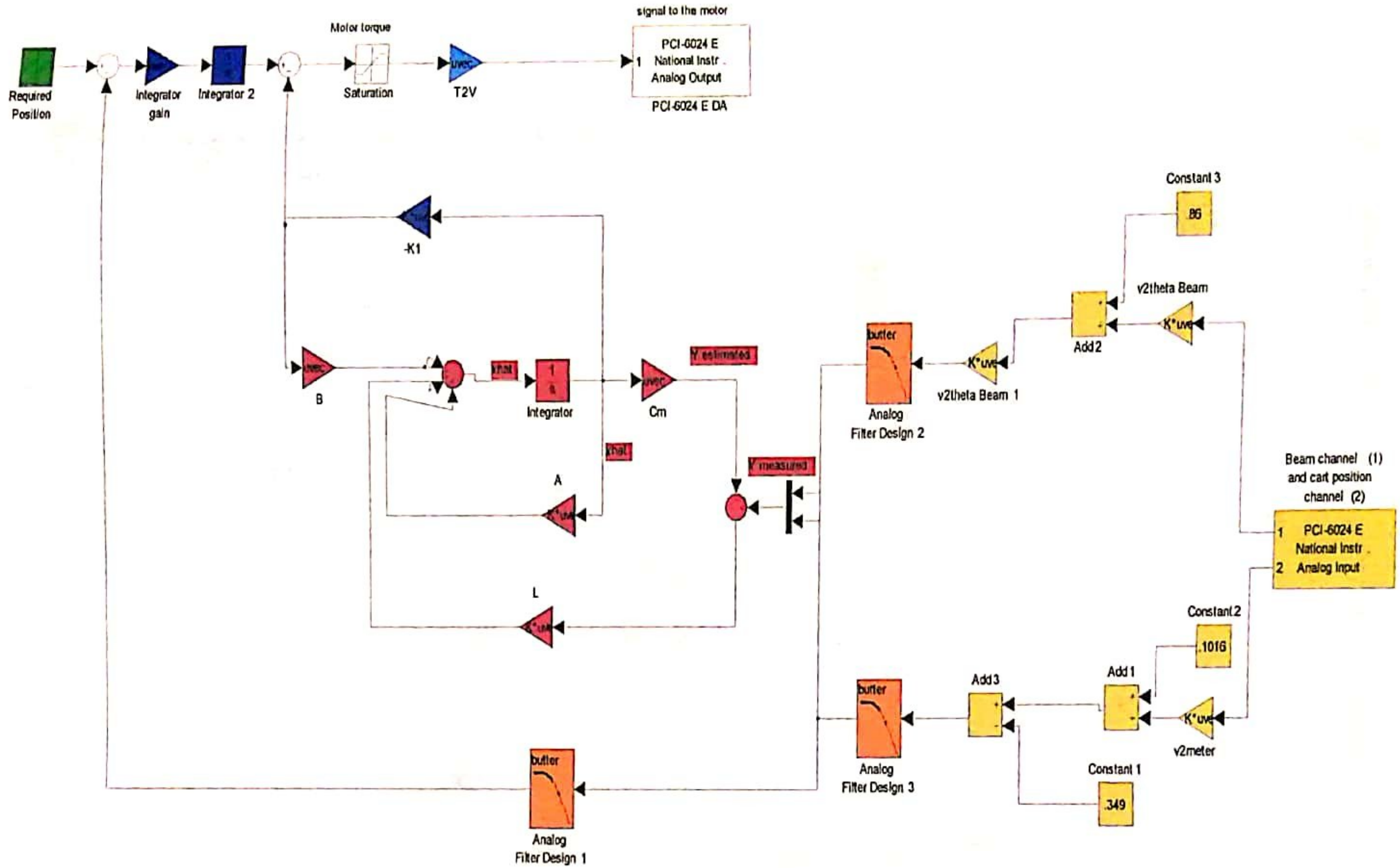


Figure 4.29 Real Beam Cart system with Observer.

4.4.3 Complete system control Beam, Cart, and Pendulum Control

Finally after solving most of the problems, the complete system has been connected, and starting to work the complete project, we build the system with observer as in Figure 4.30, and with diffrentiating the three signals as in Figure 4.31.

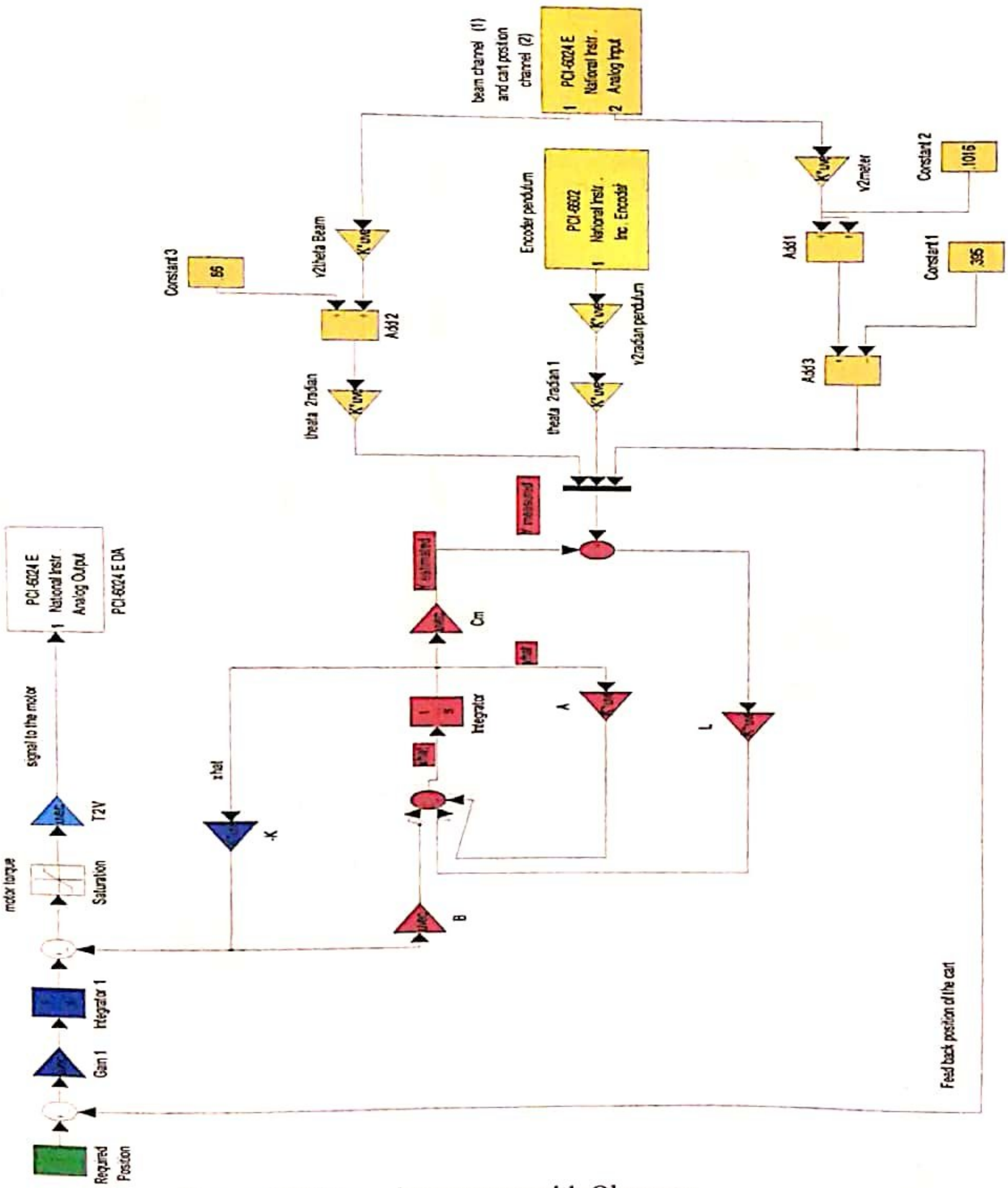


Figure 4.30 Complete system with Observer.

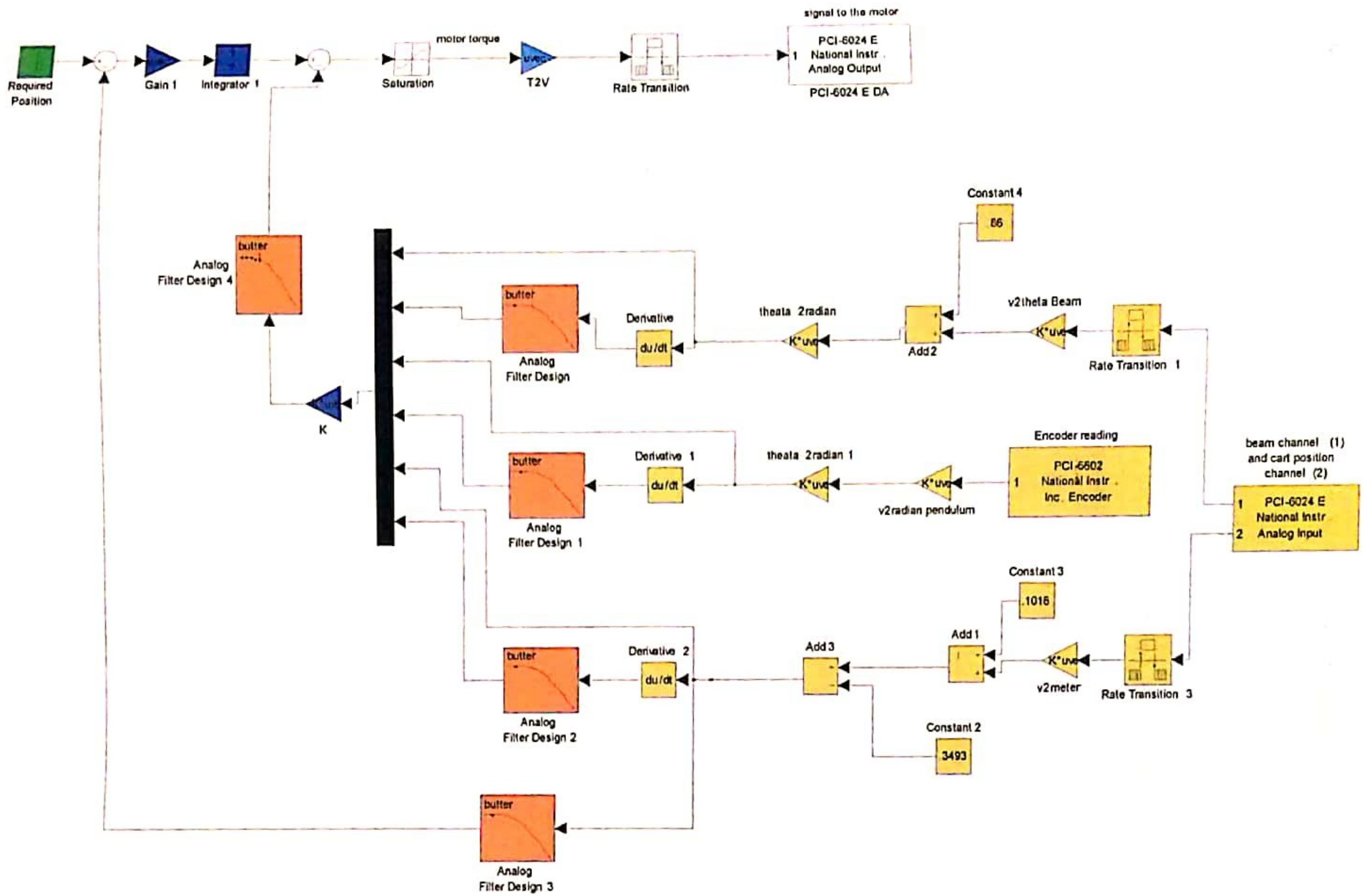


Figure 4.31 Complete system without observer, blue is the controller, green is the input, orange are filters and yellow is the sensors input.

The following figures show some of the trials to work the complete system:

- Operating the system as regulator, the cart is moved by the user to 7 cm left of the beam center, and the system return the cart to zero position within 7 seconds as shown in Figure 4.32, the torque applied to this process shown in Figure 4.33, and the beam and pendulum movement shown in Figures 4.34 and 4.35 respectively, visit the link below to see the video that describe the previous process

  http://www.youtube.com/watch?v=XBb9UzBMjsM

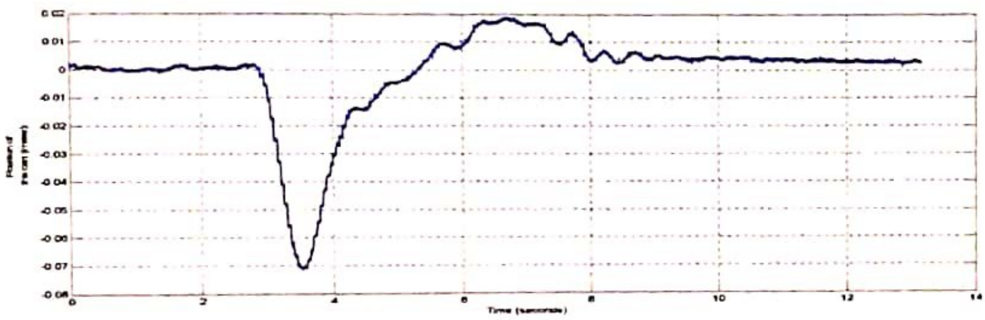


Figure 4.32 Cart motion to return to the beam center.

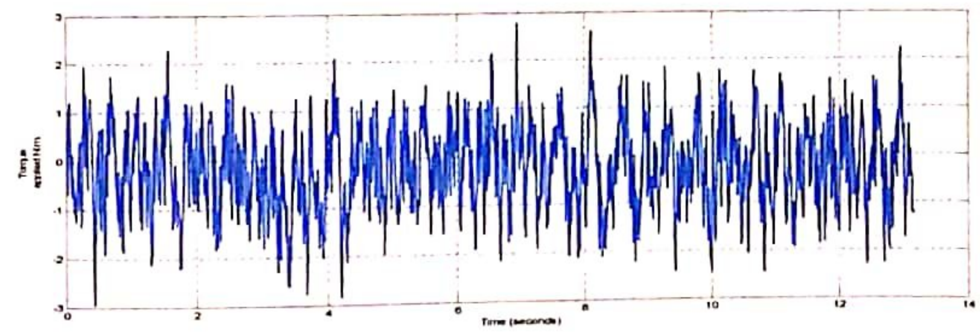


Figure 4.33 Torque applied to regulate the cart.

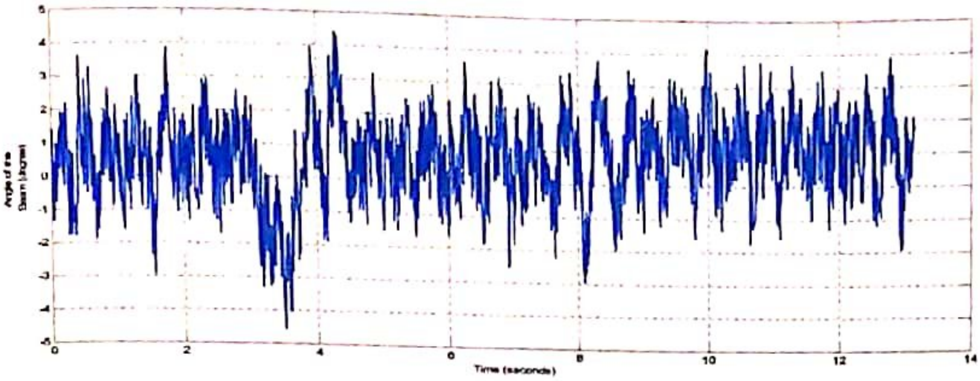


Figure 4.34 Beam movement to regulate the cart.

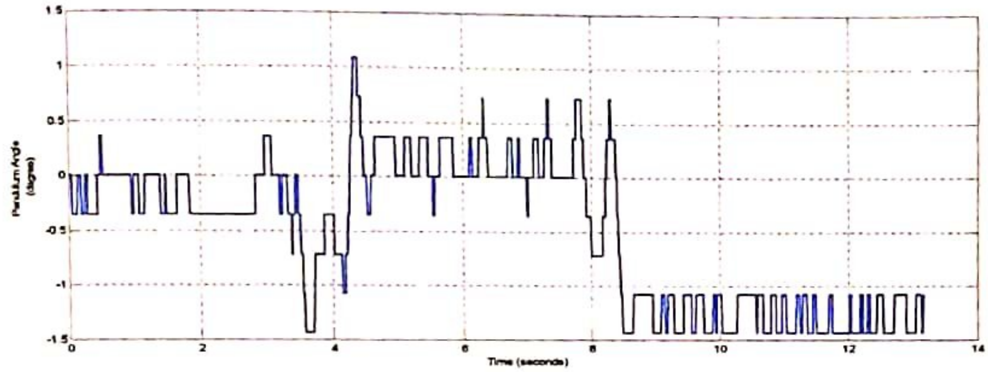


Figure 4.35 Pendulum oscillation as a result.

- Operating the system as regulator, but now a disturbance is applied to the pendulum, the Beam and cart moved to regulate the pendulum, the pendulum motion quenched after 12 seconds as shown in Figure 4.36 the torque applied to this process shown in Figure 4.37, the beam and cart movement shown in Figures 4.38 and 4.39 respectively, visit the following link to see the video of the previous process

http://www.youtube.com/watch?v=n1D2bETQm6g

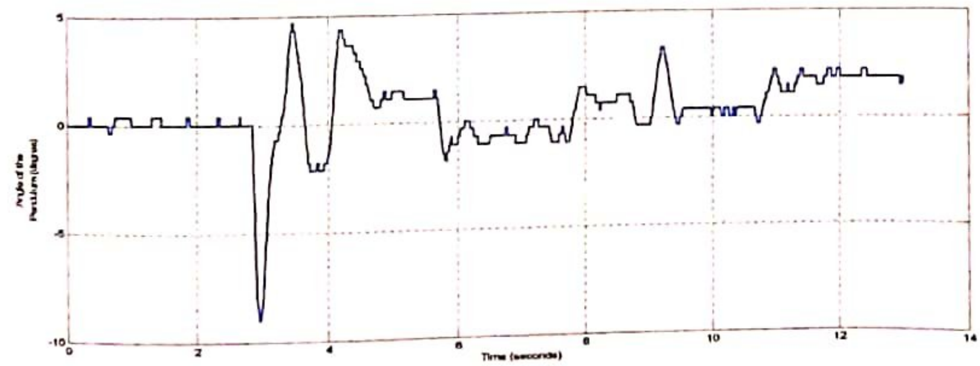


Figure 4.36 Pendulum regulation process.

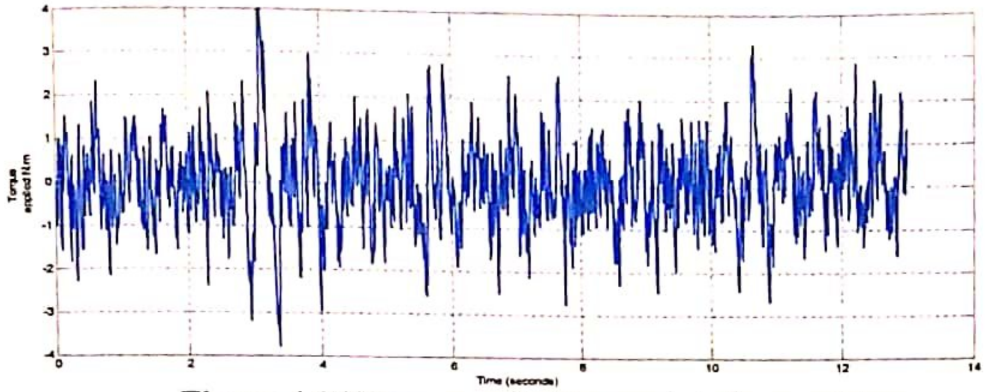


Figure 4.37 Torque applied to regulate the pendulum.

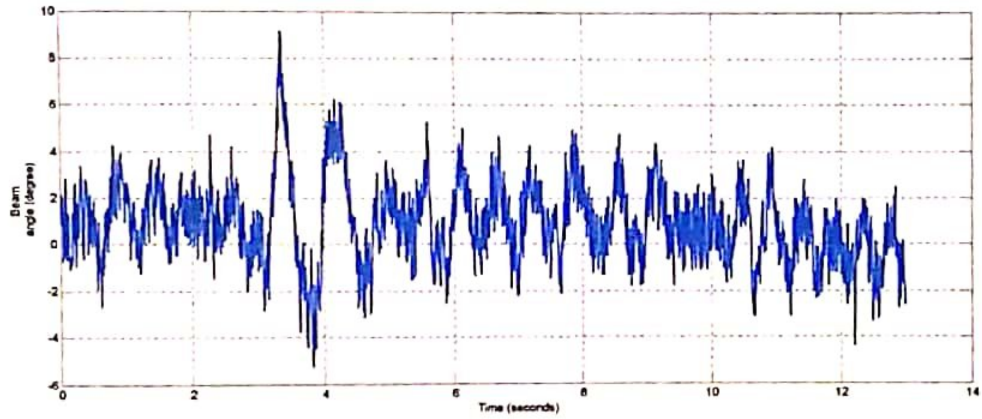


Figure 4.38 Beam movement to regulate the pendulum.

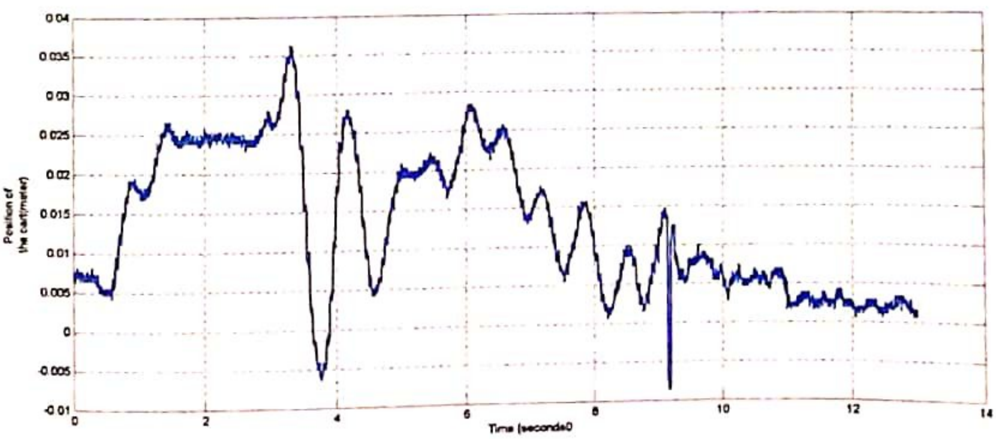


Figure 4.39 Cart motion to regulate the pendulum.

• Finally Operating as tracking system, to put the cart 20cm away from the beam center this occurred in about 17 seconds as shown in Figure 4.40, the torque applied to this process shown in Figure 4.41, the beam and pendulum movement shown in Figures 4.42 and 4.43 respectively, this complete process can be shown by visiting the following link

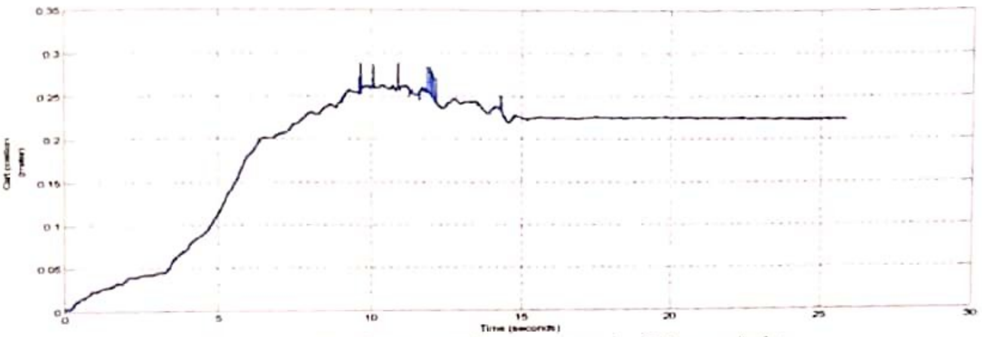


Figure 4.40 Cart motion to reach 20cm right.

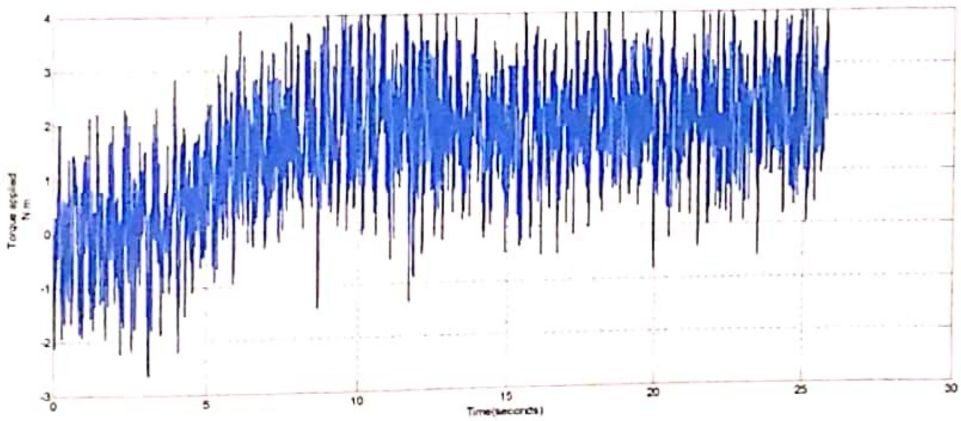


Figure 4.41 Torque applied to move the cart 20cm.

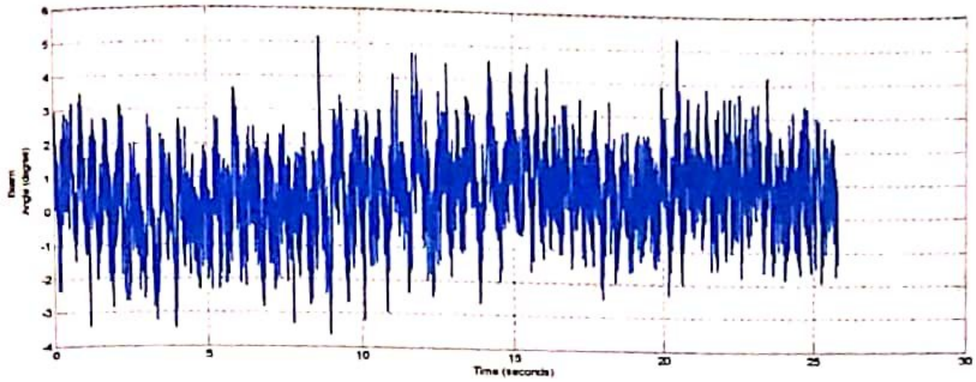


Figure 4.42 Beam motion to force the cart.

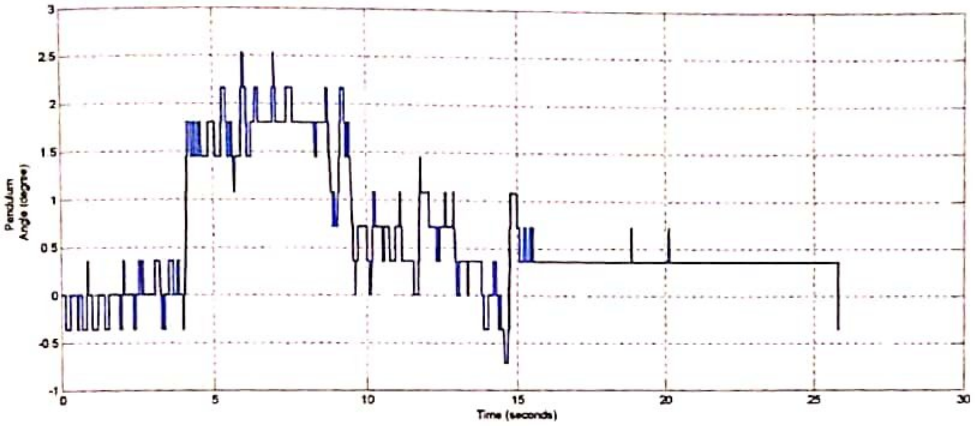


Figure 4.43 Pendulum motion as a result of the process.

Again the reason that make the torque and beam angle signals apears as in the previous figures, is the same reason that discused in the previous section 4.4.1, see Figure 4.28.

The following are links that show some trials that have been done for the system:

- Position the cart 15cm left of the beam center without pendulum

  http://www.youtube.com/watch?v=xM7lcGR5Al0

- Position the cart 20cm right of the beam center without pendulum

  http://www.youtube.com/watch?v=oLQ6Er_S2KI

- Position the cart 15cm to the left from the beam center with pendulum

  http://www.youtube.com/watch?v=zCmYj9Svi1c

4.5 Obstacles and Recommendations

In this section we will discuss some of the problems that have faced us during our way to build and run this project.

Some recommendations that we have we will talk about, in order that the students that will follow us will avoid hopefully.

Obstacles:

- The first and most important problem that has faced us is the problem of not having enough time to work at the lab, we did not have enough time at the lab, and we were not able to work anywhere but the lab, because all the devices were at that lab, and there was no way to take these devices out of the lab, the lab supervisor was so busy that we had to wait long hours before he was able to open the lab for us for an hour or two, and that caused the whole project to not be finished at the proper time.

- The second problem was that the financial aid came so late, we had to pay the whole cost of the project before we receive the financial aid.

- The lab is so noisy, that noise affected each and every signal that came in or out of the project, and that has caused us a huge difficulty.

Recommendations:

- The first recommendation is to have a supervisor of the lab that exists the whole day at the lab, in order to make the students to work easily in their project, and that will give them enough time to solve the problems that they will face.

- The second recommendation is that the financial aid must come much earlier, we know that it is not the university's fault, but we are sure that the university will do it's best to solve this problem.

- The last problem is the noise signals that exist in all the university's labs; it caused problems and will cause problems if it is not solved.

References

[1] Katsuhiko Ogata, Modern Control Engineering, Second Edition, Prentice Hall of India, New Delhi-110001, 1992.

[2] Charles L. Phillips, Digital Control System Analysisand Design, Third Edition, Pearson Education International Inc.,Upper Saddle River,New jersey 07458, 1993.

[3] Benjamin C. Kuo, Matlab Tools for Control System Analysis and Design, Prentice HallEnglewood Cliffs, NJ 07632, 1994.

[4] MATLAB Help

Appendices

The following data sheets are for devices that were used in our project.

Appendix A: Servo motor with its Driver.

Appendix B: Ultrasonic displacement sensor.

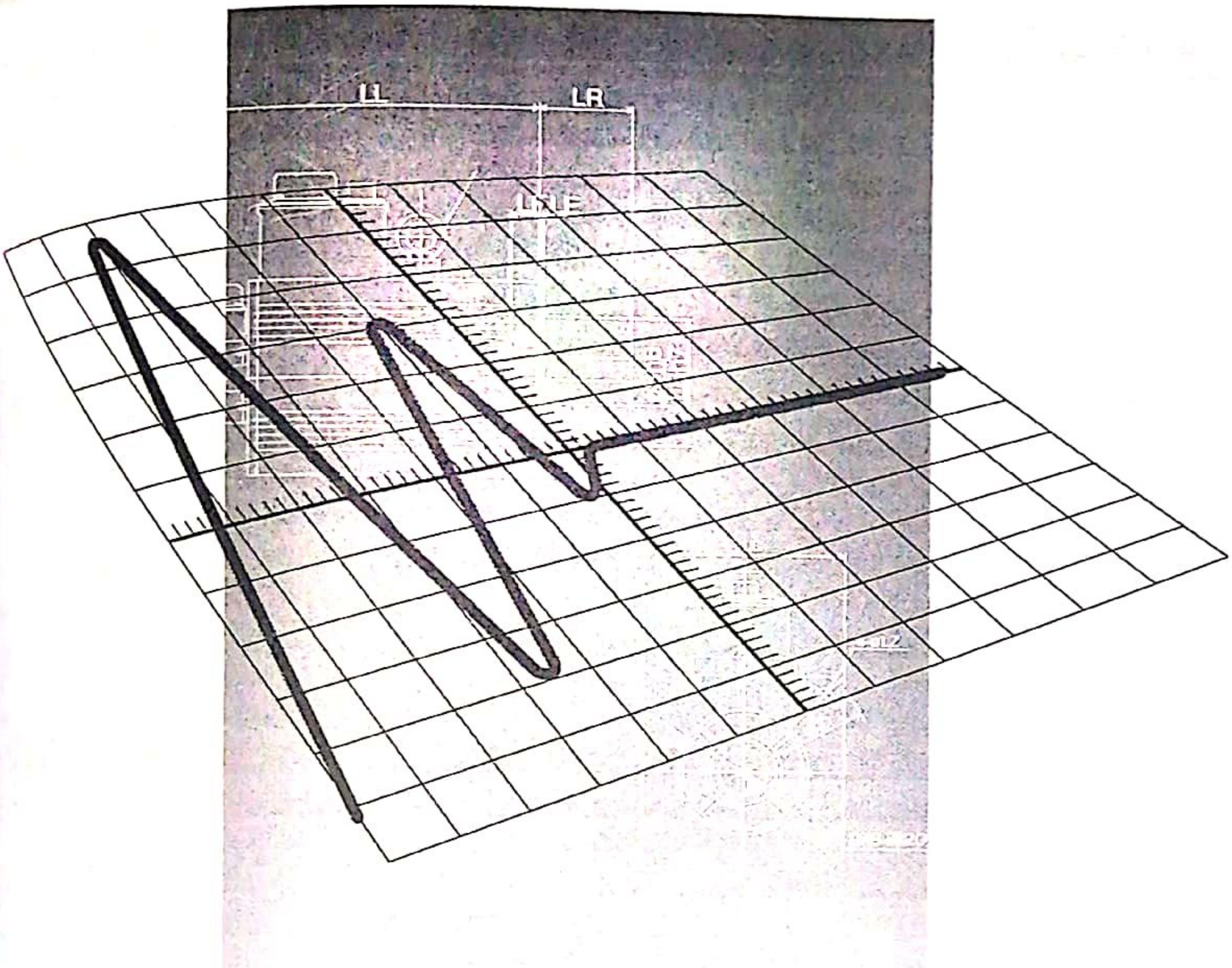
Appendix C: DAQ 6024.

Appendix D: Rotary Encoder E50S8.

Appendix E: Regulators used.

Appendix A

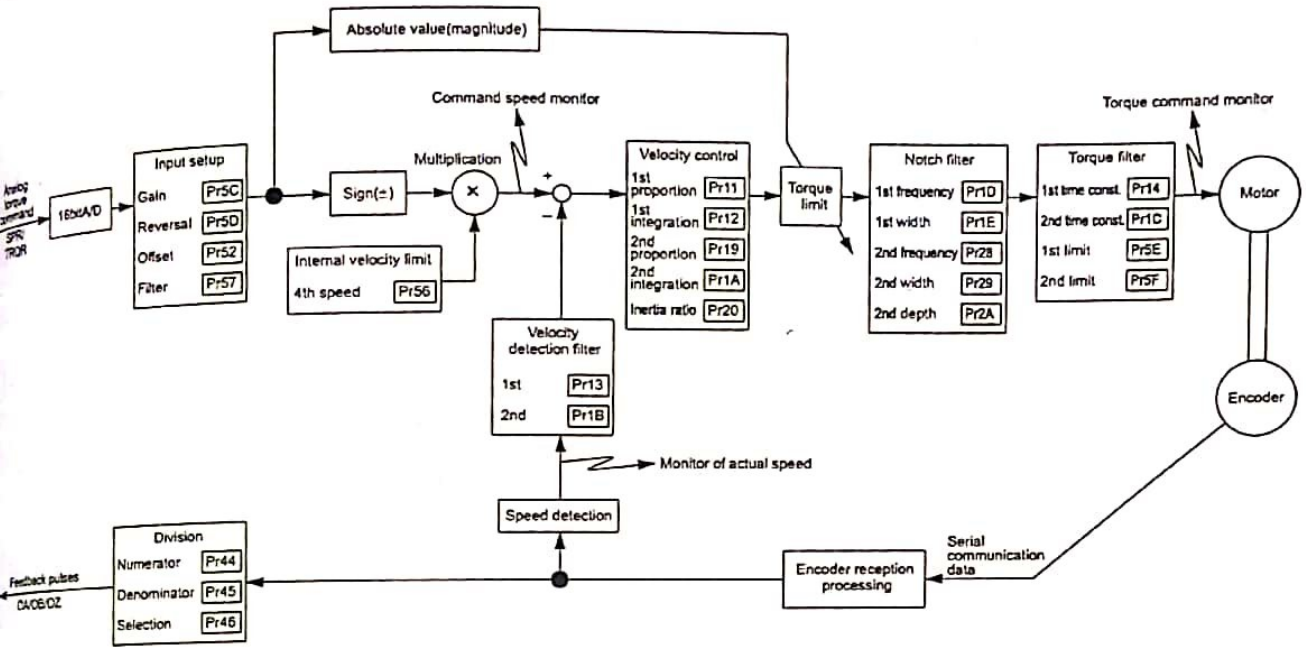
Servo motor with its Driver



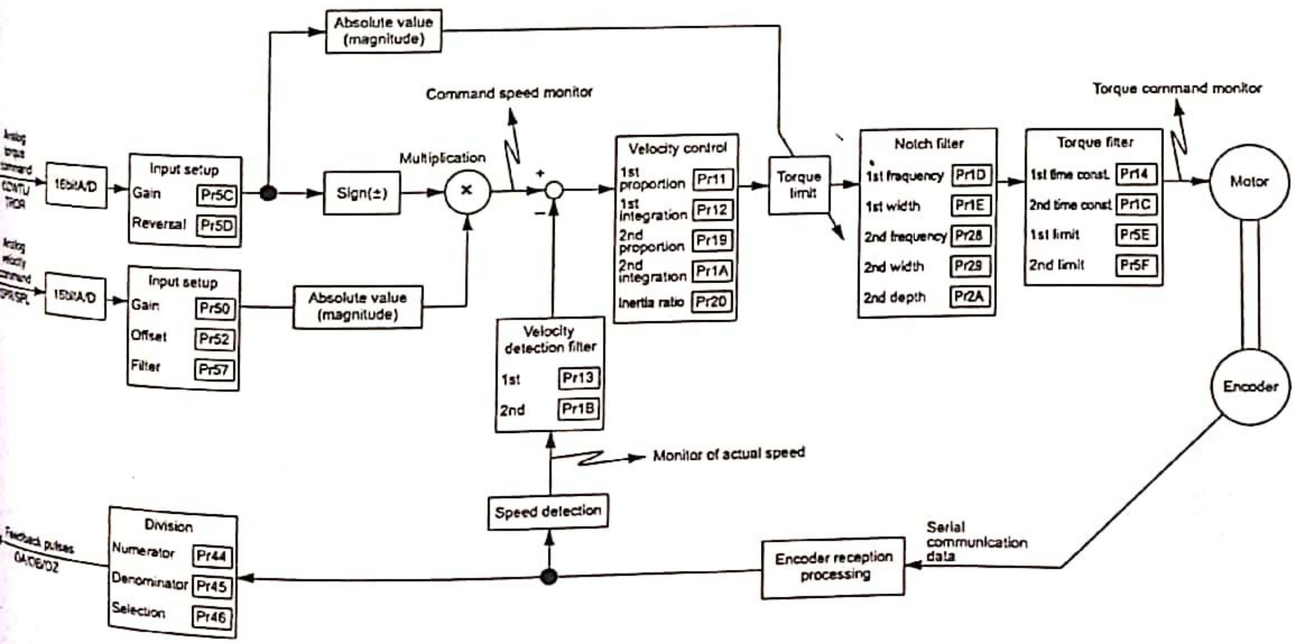
[Connection and Setup of Torque Control Mode]

Control Block Diagram of Torque Control Mode

• when Pr5B (Torque command selection) is $\boxed{0}$



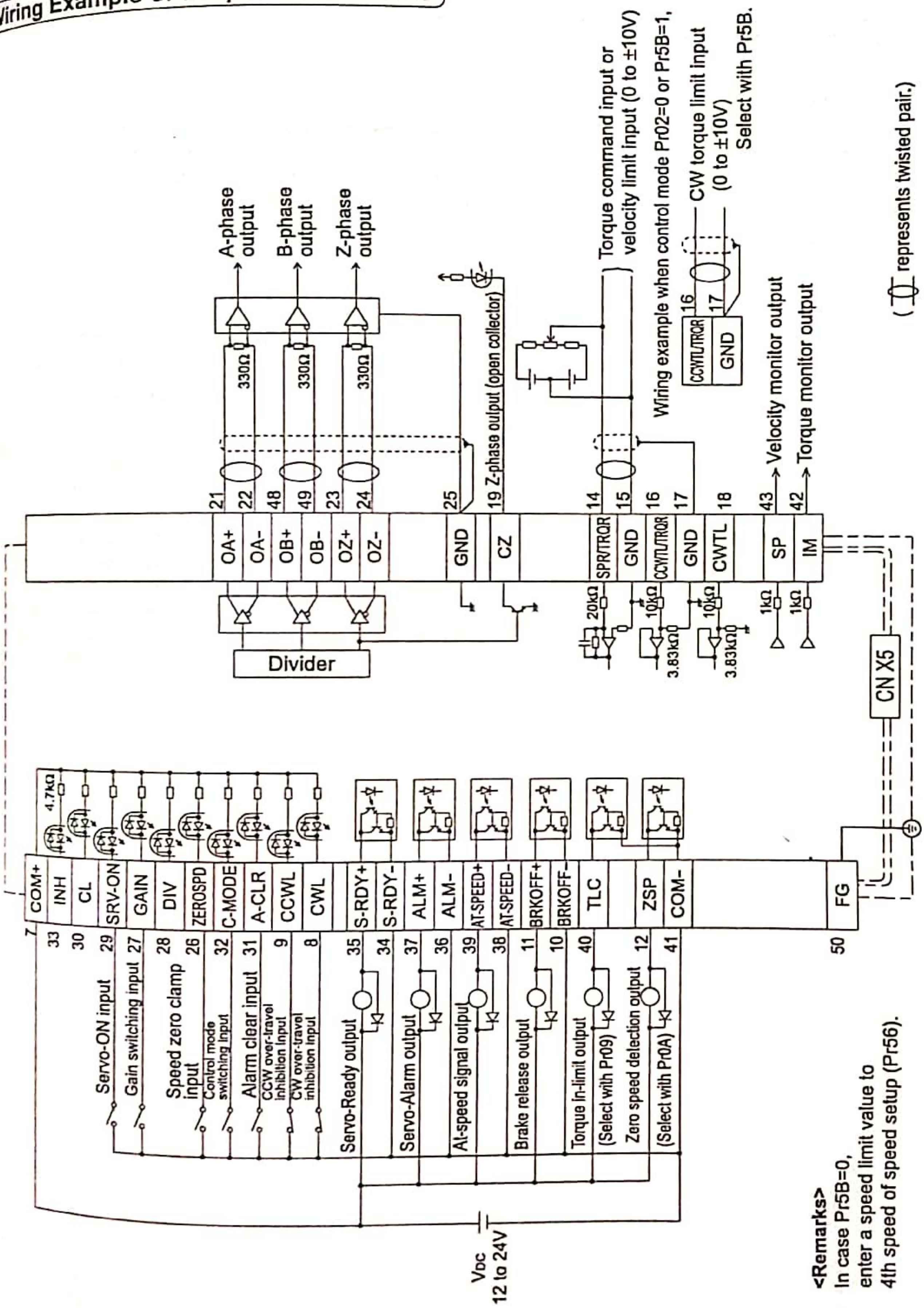
• when Pr5B (Torque command selection) is $\boxed{1}$



Wiring to the connector, CN X5 [Connection and Setup of Torque Control Mode]

Wiring Example to the Connector CN X5

Wiring Example of Torque Control Mode



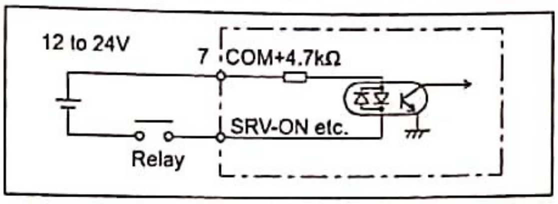
<Remarks>
In case Pr5B=0,
enter a speed limit value to
4th speed of speed setup (Pr56).

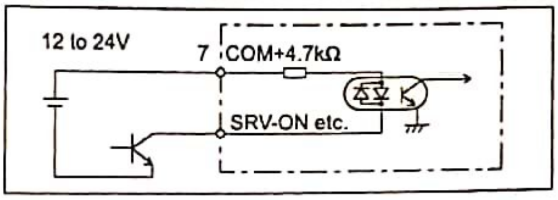
Viring to the connector, CN X5

nterface Circuit

put Circuit

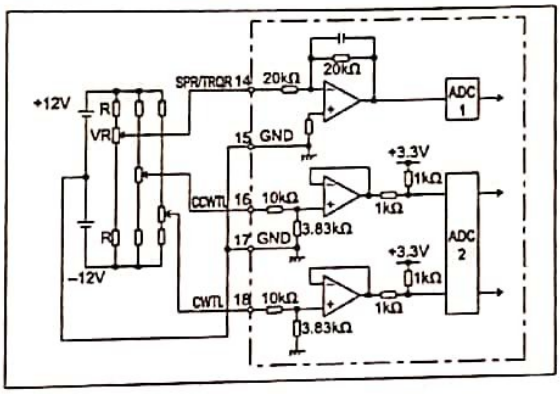
SI Connection to sequence input signals





Connect to contacts of switches and relays, or open collector output transistors.
When you use contact inputs, use the switches and relays for micro current to avoid contact failure.
Make the lower limit voltage of the power supply (12 to 24V) as 11.4V or more in order to secure the primary current for photo-couplers.

I Analog command input

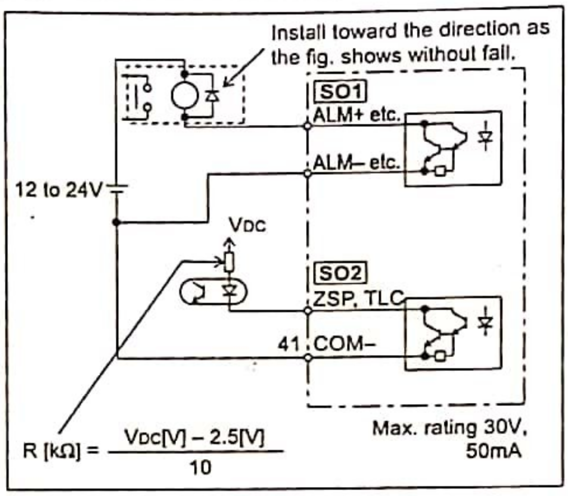


he analog command input goes through 3 routes,
PR/TRQR(Pin-14), CCWTL (Pin-16) and CWTL (Pin-18).
ax. permissible input voltage to each input is ±10V.
or input impedance of each input, refer to the right Fig.
When you compose a simple command circuit using variable sistor(VR) and register R, connect as the right Fig. shows. hen the variable range of each input is made as –10V to 0V, use VR with 2kΩ, B-char acteristics, 1/2W or larger, R th 200Ω, 1/2W or larger.
D converter resolution of each command input is as follows.
ADC1 : 16 bit (SPR/TRQR), (including 1bit for sign), ±10V
ADC2 : 10 bit (CCWTL, CWTL), 0 to 3.3V

Output Circuit

SO1 SO2 Sequence output circuit

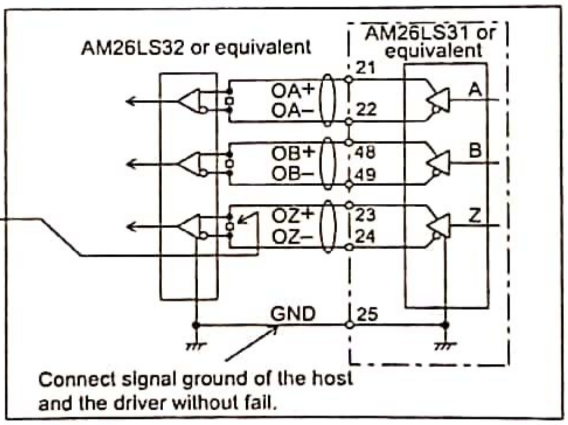
- The output circuit is composed of open collector transistor outputs in the Darlington connection, and connect to relays or photo-couplers.
- There exists collector to emitter voltage, V_{CE} (SAT) of approx. 1V at transistor-ON, due to the Darlington connection of the output or. Note that normal TTL IC cannot be directly connected since it does not meet VIL.
- There are two types of output, one which emitter side of the output transistor is independent and is connectable individually, and the one which is common to – side of the control power supply (COM–).
- If a recommended primary current value of the photo-coupler is 10mA, decide the resistor value using the formula of the right Fig.



For the recommended primary current value, refer to the data sheet of apparatus or photo-coupler to be used.

PO1 Line driver (Differential output) output

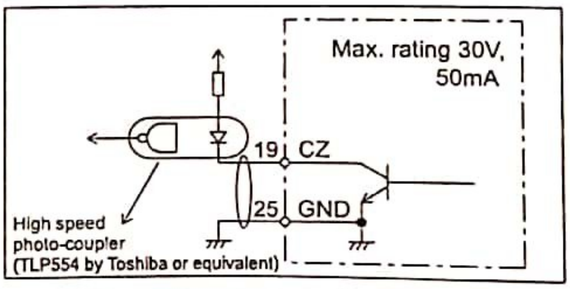
- Feeds out the divided encoder outputs (A, B and Z-phase) in differential through each line driver.
- At the host side, receive these in line receiver. Install a terminal resistor (approx. 330Ω) between line receiver inputs without fail.
- These outputs are not insulated.



represents twisted pair.

PO2 Open collector output

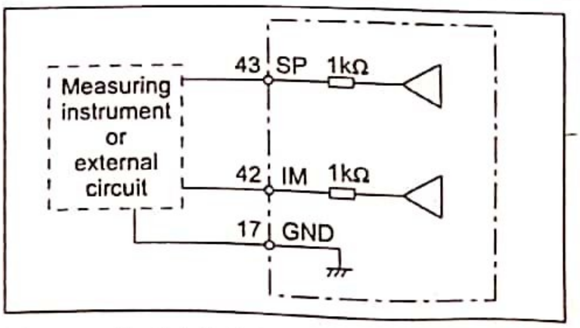
- Feeds out the Z-phase signal among the encoder signals in open collector. This output is not insulated.
- Receive this output with high-speed photo couplers at the host side, since the pulse width of the Z-phase signal is narrow.



represents twisted pair.

AO Analog monitor output

- There are two outputs, the speed monitor signal output (SP) and the torque monitor signal output (IM)
- Output signal width is ±10V.
- The output impedance is 1kΩ. Pay an attention to the input impedance of the measuring instrument or the external circuit to be connected.



<Resolution>

(1) Speed monitor output (SP)
With a setup of 6V/3000r/min (Pr07=3), the resolution converted to speed is 8r/min/16mV.

(2) Torque monitor output (IM)
With a relation of 3V/rated torque (100%), the resolution converted to torque is 0.4%/12mV.

Wiring to the connector, CN X5

Input Signal and Pin No. of the Connector, CN X5

Input Signals (common) and Their Functions

<table>
<tr><th>Title of signal</th><th>Pin No.</th><th>Symbol</th><th>Function</th><th>I/F circuit</th></tr>
<tr><td>Power supply for control signal (+)</td><td>7</td><td>COM+</td><td>• Connect + of the external DC power supply (12 to 24V).
• Use the power supply voltage of 12V ± 5% – 24V ± 5%</td><td>–</td></tr>
<tr><td>Power supply for control signal (–)</td><td>41</td><td>COM–</td><td>• Connect – of the external DC power supply (12 to 24V).
• The power capacity varies depending on a composition of I/O circuit. 0.5A or more is recommended.</td><td>–</td></tr>
<tr><td>CW over-travel inhibit input</td><td>8</td><td>CWL</td><td>• Use this input to inhibit a CW over-travel (CWL).
• Connect this so as to make the connection to COM– open when the moving portion of the machine over-travels the movable range toward CW.
• CWL input will be invalidated when you set up Pr04 (Setup of over-travel inhibit input) to 1.Default is "Invalid (1)".
• You can select the action when the CWL input is validated with the setup of up Pr66 (Sequence at over-travel inhibit). Default is "Emergency stop with dynamic brake".(Pr66=0)</td><td>SI
P.162</td></tr>
<tr><td>CCW over-travel inhibit input</td><td>9</td><td>CCWL</td><td>• Use this input to inhibit a CCW over-travel (CCWL).
• Connect this so as to make the connection to COM- open when the moving portion of the machine over-travels the movable range toward CCW.
• CWL input will be invalidated when you set up Pr04 (Setup of over-travel inhibit input) to 1.Default is "Invalid (1)".
• You can select the action when the CCWL input is validated with the setup of Pr66 (Sequence at over-travel inhibit). Default is "Emergency stop with dynamic brake".(Pr66=0)</td><td>SI
P.162</td></tr>
<tr><td>Speed zero clamp input</td><td>26</td><td>ZEROSPD</td><td>• Function varies depending on the control mode.
<table>
<tr><td>Velocity/ Torque control</td><td>• Becomes to a speed-zero clamp input (ZEROSPD).
<table>
<tr><th>Pr06</th><th>Connection to COM–</th><th>Content</th></tr>
<tr><td>0</td><td>–</td><td>ZEROSPD input is invalid.</td></tr>
<tr><td rowspan="2">1</td><td>open</td><td>Speed command is 0</td></tr>
<tr><td>close</td><td>Normal action</td></tr>
<tr><td rowspan="2">2</td><td>open</td><td>Speed command is to CCW</td></tr>
<tr><td>close</td><td>Speed command is to CW.</td></tr>
</table>
• In case Pr06 is 2 at torque control, ZERPSPD is invalid.</td></tr>
<tr><td>Position/ Full-closed control</td><td>• Becomes to an input of damping control switching (VS-SEL).
• While Pr24 (Damping filter switching selection) is 1, the 1st damping filter (Pr2B, Pr2C) will be validated when you open this input, and the 2nd damping filter (Pr2D, Pr2E) will be validated when you connect this input to COM–.</td></tr>
</table></td><td>SI
P.162</td></tr>
<tr><td>Gain switching input
or
Torque limit switching input</td><td>27</td><td>GAIN

TL-SEL</td><td>• Function varies depending on the setups of Pr30 (2nd gain setup) and Pr03 (Selection of torque limit).
<table>
<tr><th>Pr03</th><th>Pr30</th><th>Connection to COM–</th><th>Content</th></tr>
<tr><td rowspan="6">0 – 2</td><td rowspan="2">0</td><td>open</td><td>Velocity loop : PI (Proportion/Integration) action</td></tr>
<tr><td>close</td><td>Velocity loop : P (Proportion) action</td></tr>
<tr><td rowspan="4">1</td><td colspan="2">when the setups of Pr31 and Pr36 are 2</td></tr>
<tr><td>open</td><td>1st gain selection (Pr10,11,12,13 and 14)</td></tr>
<tr><td>close</td><td>2nd gain selection (Pr18,19,1A,1B and 1C)</td></tr>
<tr><td colspan="2">when the setups of Pr31 and Pr36 are other than 2
invalid</td></tr>
<tr><td>3</td><td>–</td><td colspan="2">• Input of torque limit switching (TL-SEL)
• Pr5E (Setup of 1st torque limit) will be validated when you open this input, and Pr5F (Setup of 2nd torque limit) will be validated when you connect this input to COM–.</td></tr>
</table>
• For details of 2nd gain switching function, refer to P.243 "Gain Switching Function" of Adjustment.</td><td>SI
P.162</td></tr>
</table>

<table>
<tr><th>Title of signal</th><th>Pin No.</th><th>Symbol</th><th>Function</th><th>I/F circuit</th></tr>
<tr><td>Servo-ON Input</td><td>29</td><td>SRV-ON</td><td>• Turns to Servo-ON status by connecting this input to COM–.
• Turns to Servo-OFF status by opening connection to COM–, and current to the motor will be shut off.
• You can select the dynamic brake action and the deviation counter clearing action at Servo-OFF with Pr69 (Sequence at Servo-OFF).
<Caution>
1.Servo-ON input becomes valid approx. 2 sec after power-on. (see P.42, "Timing Chart" of Preparation.)
2.Never run/stop the motor with Servo-ON/OFF.
3.After shifting to Servo-ON, allow 100ms or longer pause before entering the pulse command.</td><td>SI
P.162</td></tr>
<tr><td>Alarm clear input</td><td>31</td><td>A-CLR</td><td>• You can release the alarm status by connecting this to COM– for more than 120ms.
• The deviation counter will be cleared at alarm clear.
• There are some alarms which cannot be released with this input. For details, refer to P.252, "Protective Function " of When in Trouble.</td><td>SI
P.162</td></tr>
<tr><td>Control mode switching Input</td><td>32</td><td>C-MODE</td><td>• You can switch the control mode as below by setting up Pr02 (Control mode setup) to 3-5.
<table>
<tr><th>Pr02 setup</th><th>Open (1st)</th><th>Connection to COM– (2nd)</th></tr>
<tr><td>3</td><td>Position control</td><td>Velocity control</td></tr>
<tr><td>4</td><td>Position control</td><td>Torque control</td></tr>
<tr><td>5</td><td>Velocity control</td><td>Torque control</td></tr>
</table>
<Caution>
Depending on how the command is given at each control mode, the action might change rapidly when switching the control mode with C-MODE. Pay an extra attention.</td><td>SI
P.162</td></tr>
</table>

Wiring to the connector, CN X5

Input Signals (Analog Command) and Their Functions

<table>
<tr><th>Title of signal</th><th>Pin No.</th><th>Symbol</th><th>Function</th><th>I/F circuit</th></tr>
<tr>
<td>Torque command input, or Speed limit input</td>
<td>14</td>
<td>TRQR

SPL</td>
<td>
• Function varies depending on control mode.
<table>
<tr><th>Pr02</th><th>Control mode</th><th>Function</th></tr>
<tr>
<td>2
4</td>
<td>Torque cortrol

Position/ Torque</td>
<td>• Function varies depending on Pr5B (Selection of torque command)
<table>
<tr><th>Pr5B</th><th>Content</th></tr>
<tr><td>0</td><td>• Torque command (TRQR) will be selected.
• Set up the torque (TRQR) gain, polarity offset and filter with;
Pr5C (Torque command input gain)
Pr5D (Torque command input reversal)
Pr52 (Speed command offset)
Pr57 (Speed command filter setup)</td></tr>
<tr><td>1</td><td>• Speed limit (SPL) will be selected.
• Set up the speed limit (SPL) gain, offset and filter with;
Pr50 (Speed command input gain)
Pr52 (Speed command offset)
Pr57 (Speed command filter setup)</td></tr>
</table>
</td>
</tr>
<tr>
<td>5</td>
<td>Velocity/ Torque</td>
<td>• Function varies depending on Pr5B (Selection of torque command)
<table>
<tr><th>Pr5B</th><th>Content</th></tr>
<tr><td>0</td><td>• This input becomes invalid.</td></tr>
<tr><td>1</td><td>• Speed limit (SPL) will be selected.
• Set up the speed limit (SPL) gain, offset and filter with;
Pr50 (Speed command input gain)
Pr52 (Speed command offset)
Pr57 (Speed command filter setup)</td></tr>
</table>
</td>
</tr>
<tr><td>Others</td><td>Other control mode</td><td>• This input is invalid.</td></tr>
</table>
•The resolution of the A/D converter used in this input is 16 bit (including 1 bit for sign).
± 32767 (LSB) = ± 10[V], 1[LSB] ≒ 0.3[mV]
</td>
<td>AI
P.162</td>
</tr>
</table>

Function becomes valid when the control mode with underline (▭ / ▭) is selected while the switching mode is used in the control mode in table.

<table>
<tr><th>Title of signal</th><th>Pin No.</th><th>Symbol</th><th>Function</th><th>I/F circuit</th></tr>
<tr><td>Torque command input</td><td>16</td><td>TRQR</td><td>
• Function varies depending on Pr02 (Control mode setup).
<table>
<tr><th>Pr02</th><th>Control mode</th><th>Function</th></tr>
<tr><td>2
4</td><td>Torque Control
Position/Torque</td><td>• Function varies depending on Pr5B (Selection of torque command)
<table>
<tr><th>Pr5B</th><th>Content</th></tr>
<tr><td>0</td><td>This input becomes invalid.</td></tr>
<tr><td>1</td><td>• Torque command input (TRQR) will be selected.
• Set up the gain and polarity of the command with;
Pr5C (Torque command input gain)
Pr5D (Torque command input reversal)
• Offset and filter cannot be set up.</td></tr>
</table></td></tr>
<tr><td>5</td><td>Velocity/ Torque</td><td>• Becomes to the torque command input (TRQR).
• Set up the gain and polarity of the command with;
Pr5C (Torque command input gain)
Pr5D (Torque command input reversal)
• Offset and filter cannot be set up.</td></tr>
<tr><td>4
5
Other</td><td>Position/Torque
Velocity/Torque
Other control mode</td><td>• Becomes to the analog torque limit input to CCW (CCWTL).
• Limit the CCW-torque by applying positive voltage (0 to +10V) (Approx.+3V/rated torque)
• Invalidate this input by setting up Pr03 (Torque limit selection) to other than 0.</td></tr>
</table>
• Resolution of A/D converter used in this input is 16 bit (including 1 bit for sign).
± 511 [LSB] = ± 11.9[V], 1 [LSB] ≒ 23[mV]
</td><td>AI
P.162</td></tr>
</table>

*Function becomes valid when the control mode with underline (/) is selected while the switching mode is used in the control mode in table.

<Remark>

Do not apply more than ±10V to analog command inputs of SPR/TRQR/SPL

Do not apply more than ±10V to analog command input of TRQR.

Wiring to the connector, CN X5

Output signal and Pin No. of the Connector, CN X5

Output Signals (Common) and Their Functions

Title of signal	Pin No	Symbol	Function	I/F circuit
External brake release signal	11 10	BRKOFF+ BRKOFF–	• Feeds out the timing signal which activates the electromagnetic brake of the motor. • Turns the output transistor ON at the release timing of the electro-magnetic brake. • You can set up the output timing of this signal with Pr6A (Setup of mechanical brake action at stall) and Pr6B (Setup of mechanical brake action at motion). For details, refer to P42, "Timing Chart" of Preparation.)	SO1 P.163
Servo-Ready output	35 34	S-RDY+ S-RDY–	• This signal shows that the driver is ready to be activated. • Output transistor turns ON when both control and main power are ON but not at alarm status.	SO1 P.163
Servo-Alarm output	37 36	ALM+ ALM–	• This signal shows that the driver is in alarm status.. • Output transistor turns ON when the driver is at normal status, and turns OFF at alarm status.	SO1 P.163
Speed arrival output	39 38	AT-SPEED+ AT-SPEED–	• Function varies depending on the control mode. **Position control**: • Output of positioning complete (COIN) • The output transistor will turn ON when the absolute value of the position deviation pulse becomes smaller than the setup value of Pr60 (Positioning complete range). • You can select the feeding out method with Pr63 (Setup of positioning complete output). **Full-closed control**: • Output of full-closed positioning complete (EX-COIN) • The output transistor will turn ON when the absolute value of full-closed-position deviation pulse becomes smaller than the setup value of Pr60 (Positioning complete range). • You can select the feeding out method with Pr63 (Setup of positioning complete output). **Velocity/ Torque control**: • Output at-speed (speed arrival) (AT-SPEED) • The output transistor will turn ON when the actual motor speed exceeds the setup value of Pr62 (In-speed).	SO1 P.163
Zero-speed detection output signal	12 (41)	ZSP (COM–)	• Content of the output signal varies depending on Pr0A (Selection of ZSP output). • Default is 1, and feeds out the zero speed detection signal. • For details, see the table below, "Selection of TLC,ZSP output".	SO2 P.163
Torque in-limit signal output	40 (41)	TLC (COM–)	• Content of the output signal varies depending on Pr09 (Selection of TLC output). • Default is 1, and feeds out the torque in-limit signal. • For details, see the table below, "Selection of TLC,ZSP output".	SO2 P.163

• Selection of TCL and ZSP outputs

	X5 TLC : Output of Pin-40 / X5 ZSP : Output of Pin-12
0	• Torque in-limit output (Default of X5 TLC Pr09) The output transistor turns ON when the torque command is limited by the torque limit during Servo-ON.
1	• Zero-speed detection output (Default of X5 ZSP Pr0A) The output transistor turns ON when the motor speed falls under the preset value with Pr61.
2	• Alarm signal output The output transistor turns ON when either one of the alarms is triggered, over-regeneration alarm, overload alarm, battery alarm, fan-lock alarm or external scale alarm.
3	• Over-regeneration alarm The output transistor turns ON when the regeneration exceeds 85% of the alarm trigger level of the regenerative load protection.
4	• Over-load alarm The output transistor turns ON when the load exceeds 85% of the alarm trigger level of the overload alarm.
5	• Battery alarm The output transistor turns ON when the battery voltage for absolute encoder falls lower than approx. 3.2V.
6	• Fan-lock alarm The output transistor turns ON when the fan stalls for longer than 1s.
7	• External scale alarm The output transistor turns ON when the external scale temperature exceeds 65°, or signal intensity is not enough (adjustment on mounting is required). Valid only at the full-closed control.
8	• In-speed (Speed coincidence) output The output transistor turns ON when the difference between the actual motor speed and the speed command before acceleration/deceleration reaches within the preset range with Pr61. Valid only at the velocity and torque control.

Output Signals (Pulse Train) and Their Functions

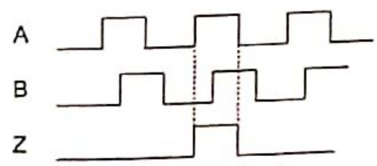
Title of signal	Pin No	Symbol	Function	I/F circuit
A-phase output	21	OA +	• Feeds out the divided encoder signal or external scale signal (A, B, Z-phase) in differential. (equivalent to RS422) • You can set up the division ratio with Pr44 (Numerator of pulse output division) and Pr45 (Denominator of pulse output division) • You can select the logic relation between A-phase and B-phase, and the output source with Pr46 (Reversal of pulse output logic). • When the external scale is made as an output source, you can set up the interval of Z-phase pulse output with Pr47 (Setup of external scale Z-phase). • Ground for line driver of output circuit is connected to signal ground (GND) and is not insulated. • Max. output frequency is 4Mpps (after quadrupled)	PO1 P.163
	22	OA –		
B-phase output	48	OB +		
	49	OB –		
Z-phase output	23	OZ +		
	24	OZ –		
Z-phase output	19	CZ	• Open collector output of Z-phase signal • The emitter side of the transistor of the output circuit is connected to the signal ground (GND) and is not insulated.	PO2 P.163

<Note>

• When the output source is the encoder

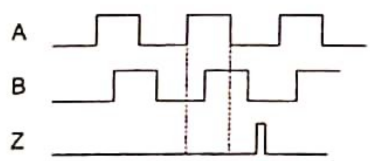
• If the encoder resolution $\times \frac{Pr44}{Pr45}$ is multiple of 4, Z-phase will be fed out synchronizing with A-phase. In other case, the Z-phase width will be equal to the encoder resolution, and will not synchronize with A-phase because of narrower width than that of A-phase.

when the encoder resolution $\frac{Pr44}{Pr45}$ is multiple of 4,



synchronized

when the encoder resolution $\frac{Pr44}{Pr45}$ is not multiple of 4,



not-synchronized

• In case of the 5-wire, 2500P/r incremental encoder, the signal sequence might not follow the above fig. until the first Z-phase is fed out. When you use the pulse output as the control signal, rotate the motor one revolution or more to make sure that the Z-phase is fed out at least once before using.

Wiring to the connector, CN X5

Output Signals (Analog) and Their Functions

<table>
<tr><th>Title of signal</th><th>Pin No</th><th>Symbol</th><th>Function</th><th>I/F circuit</th></tr>
<tr><td>Torque monitor signal output</td><td>42</td><td>IM</td><td>
• The content of output signal varies depending on Pr08 (Torque monitor (IM) selection).
• You can set up the scaling with Pr08 value.
<table>
<tr><th>Pr08</th><th>Content of signal</th><th>Function</th></tr>
<tr><td>0, 11,12</td><td>Torque command</td><td>• Feeds out the voltage in proportion to the motor torque command with polarity.
+ : generates CCW torque
– : generates CW torque</td></tr>
<tr><td>1 – 5</td><td>Positional deviation</td><td>• Feeds out the voltage in proportion to the positional deviation pulse counts with polarity.
+ : positional command to CCW of motor position
– : positional command to CW of motor position</td></tr>
<tr><td>6 –10</td><td>Full-closed deviation</td><td>• Feeds out the voltage in proportion to the full-closed deviation pulse counts with polarity.
+ : positional command to CCW of external scale position
– : positional command to CW of external scale position</td></tr>
</table>
</td><td>AO
P.163</td></tr>
<tr><td>Speed monitor signal output</td><td>43</td><td>SP</td><td>
• The content of the output signal varies depending on Pr07 (Speed monitor (IM) selection).
• You can set up the scaling with Pr07 value.
<table>
<tr><th>Pr07</th><th>Control mode</th><th>Function</th></tr>
<tr><td>0 – 4</td><td>Motor speed</td><td>• Feeds out the voltage in proportion to the motor speed with polarity. + : rotates to CCW
– : rotates to CW</td></tr>
<tr><td>5 – 9</td><td>Command speed</td><td>• Feeds out the voltage in proportion to the command speed with polarity.
+ : rotates to CCW
– : rotates to CW</td></tr>
</table>
</td><td>AO
P.163</td></tr>
</table>

Output Signals (Others) and Their Functions

Title of signal	Pin No	Symbol	Function	I/F circuit
Signal ground	13,15, 17,25	GND	• Signal ground • This output is insulated from the control signal power (COM–) inside of the drivder.	–
Frame ground	50	FG	• This output is connected to the earth terminal inside of the drivder.	–

Trial Run (JOG run) at Velocity Control Mode

Inspection Before Trial Run

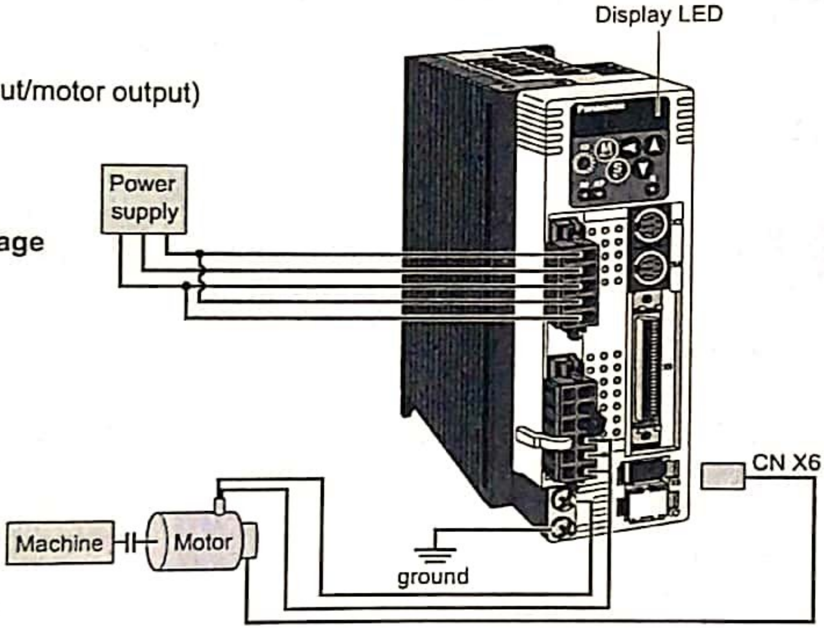
(1) Wiring inspection
- Miswiring
  (Especially power input/motor output)
- Short/Earth
- Loose connection

(2) Check of power/voltage
- Rated voltage

(3) Fixing of the motor
- Unstable fixing

(4) Separation from mechanical system

(5) Release of the brake



Trial Run by Connecting the Connector, CN X5

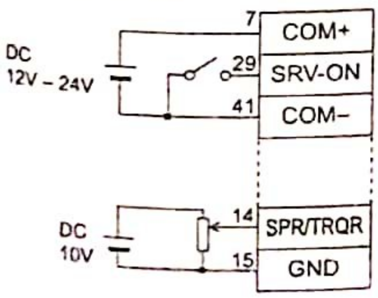
1) Connect the CN X5.
2) Enter the power (DC12-24V) to control signal (COM+, COM–)
3) Enter the power to the driver.
4) Confirm the default values of parameters.
5) Set a lower value to Pr56 (4th speed of speed setup).
6) Enrgize the motor by connecting the Servo-ON input (SRV-ON, CN X5, Pin-29) and COM– (Pin-41 of CN X5) to turn to Servo-ON status.
7) Confirm that the motor runs as per the setup of Pr56 by applying DC voltage (positive/negative) between the torque command input (Pin-14 of CN X5) and GND (Pin-41 of CN X5).
8) If you want to change the torque magnitude, direction and velocity limit value against the command voltage, set up the following parametes.

Pr56 : 4th speed of speed setup
Pr5C : Torque command input gain
Pr5D : Torque command input reversal

Refer to P.183, "Parameter Setup-Paramteres for Velocity and Torque Control".

9) If the motor does not run correctly, refer to P.68, "Display of factor for No-motor running" of Preparation.

Wiring Diagram



In case of one way running

For bi-directional running (CW/CCW), provide a bipolar power supply.

Parameter

PrNo.	Title	Setup value
02	Setup of control mode	2
04	Invalidation of over-travel inhibit input	1
06	Selection of ZEROSPD	0
56	4th speed of speed setup	lower value
5B	Selection of torque command	0
5C	Torque command input gain	Set up as required
5D	Torque command input reversal	

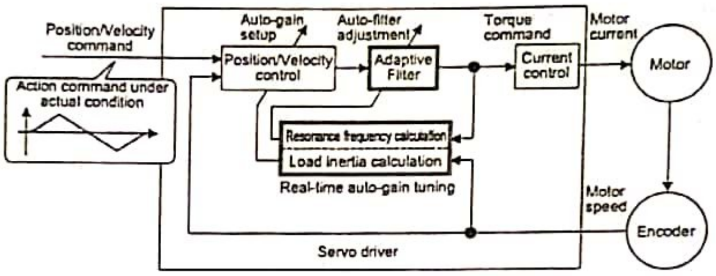
Input signal status

No.	Title of signal	Monitor display
0	Servo-ON	+A
5	Speed zero clamp	–

Real-Time Auto-Gain Tuning

Outline

The driver estimates the load inertia of the machine in real time, and automatically sets up the optimum gain responding to the result. Also the driver automatically suppress the vibration caused by the resonance with an adaptive filter.



Applicable Range

- Real-time auto-gain tuning is applicable to all control modes.

Caution

Real-time auto-gain tuning may not be executed properly under the conditions described in the right table. In these cases, use the normal mode auto-gain tuning (refer to P.236 of Adjustment), or execute a manual gain tuning. (refer to P.240, of Adjustment)

	Conditions which obstruct real-time auto-gain tuning
Load inertia	• Load is too small or large compared to rotor inertia. (less than 3 times or more than 20 times) • Load inertia change too quickly. (10 [s] or less)
Load	• Machine stiffness is extremely low. • Chattering such as backlash exists.
Action pattern	• Motor is running continuously at low speed of 100 [r/min] or lower. • Acceleration/deceleration is slow (2000[r/min] per 1[s] or low). • Acceleration/deceleration torque is smaller than unbalanced weighted/viscous friction torque. • When speed condition of 100[r/min] or more and acceleration/deceleration condition of 2000[r/min] per 1[s] are not maintained for 50[ms].

How to Operate

(1) Bring the motor to stall (Servo-OFF).
(2) Set up Pr21 (Real-time auto-gain tuning mode setup) to 1-7. Default is 1.

Setup value	Real-time auto-gain tuning	Varying degree of load inertia in motion
0	(not in use)	–
<1>,4,7	normal mode	no change
2, 5		slow change
3, 6		rapid change

• When the varying degree of load inertia is large, set up 3.

(3) Set up Pr22 (Machine stiffness at real-time auto-gain tuning) to 0 or smaller value.
(4) Turn to Servo-ON to run the machine normally.
(5) Gradually increase Pr22 (Machine stiffness at real-time auto-gain tuning) when you want to obtain better response. Lower the value (0 to 3) when you experience abnormal noise or oscillation.
(6) Write to EEPROM when you want to save the result.

Insert the console connector to CN X6 of the driver, then turn on the driver power. — r 0

Setup of parameter, Pr21

Press (S). — dP_SPd

Press (M). — PA_ 00

Match to the parameter No. to be set up with (▲)(▼). (Here match to Pr21.) — PA_ 21

Press (S). — 1

Change the setup with (▲)(▼).

Press (S). — PA_ 21

Setup of parameter, Pr22

Match to Pr22 with (▲). — PA_ 22

Press (S). — 4 (default values)

Numeral increases with (▲),

and decreases with (▼).

Press (S).

Writing to EEPROM

Press (M). — EE_SEt

Press (S). — EEP -

Bars increase as the right fig. shows by keep pressing (▲) (approx. 5sec). — EEP -- → ------

Writing starts (temporary display). — StArt

Finish — FinISh / rESEt: Writing completes; Error: Writing error occurs

Return to SELECTION display after writing finishes, referring to "Structure of each mode"(P.60 and 61 of Preparation).

Parameters Which Are Automatically Set Up.

Following parameters are automatically adjusted.

PrNo.	Title
11	1st gain of velocity loop
12	1st time constant of velocity loop integration
13	1st filter of velocity detection
14	1st time constant of torque filter
19	2nd gain of velocity loop
1A	2nd time constant of velocity loop integration
1B	2nd filter of speed detection
1C	2nd time constant of torque filter
20	Inertia ratio

Also following parameters are automatically set up.

PrNo.	Title	Setup value
30	2nd gain setup	1
31	1st mode of control switching	0
32	1st delay time of control switching	30
33	1st level of control switching	50
34	1st hysteresis of control switching	33
36	2nd mode of control switching	0

<Notes>

- When the real-time auto-gain tuning is valid, you cannot change parameters which are automatically adjusted.
- Pr31 becomes 10 at position or full closed control and when Pr21 (Setup of Real-Time Auto-Gain Tuning Mode) is 1 to 6, and becomes 0 in other cases.

Cautions

(1) After the start-up, you may experience abnormal noise and oscillation right after the first Servo-ON, or when you increase the setup of Pr22 (Seleon of machine stiffness at real-time auto-gain tuning), until load inertia is identified (estimated) or adaptive filter is stabilized, however, these are not failures as long as they disappear immediately. If they persist over 3 reciprocating operations, take the following measures in possible order.

1)Write the parameters which have given the normal operation into EEPROM.

2)Lower the setup of Pr22 (Selection of machine stiffness at real-time auto-gain tuning).

3)Set up both Pr21 (Setup of real-time auto-gain tuning) and Pr23 (Setup of adaptive filter mode) to 0, then set up other value than 0. (Reset of inertia estimation and adaptive action)

4)Invalidate the adaptive filter by setting up Pr23 (Setup of adaptive filter mode setup) to 0, and set up notch filter manually.

(2) When abnormal noise and oscillation occur, Pr20 (Inertia ratio) or Pr2F (Adaptive filter frequency) might have changed to extreme values. Take the same measures as the above in these cases.

(3) Among the results of real-time auto-gain tuning, Pr20 (Inertia ratio) and Pr2F (Adaptive filter frequency) will be wtitten to EEPROM every 30 minutes. When you turn on the power again, auto-gain tuning will be exrcuted using the latest data as initial values.

(4) When you validate the real-time auto-gain tuning, Pr27 (Setup of instantaneous speed observer) will be invalidated automatically.

(5) The adaptive filter is normally invalidated at torque control, however, when you select torque control while you set up Pr02 (Control mode setup) to 4 and 5, the adaptive filter frequency before mode switching will be held.

(6) During the trial run and frequency characteristics measurement of "PANATERM®", the load inertia estimation will be invalidated.

Connection and Setup of Torque Control Mode

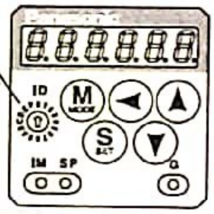
Parameter Setup

Parameters for Functional Selection

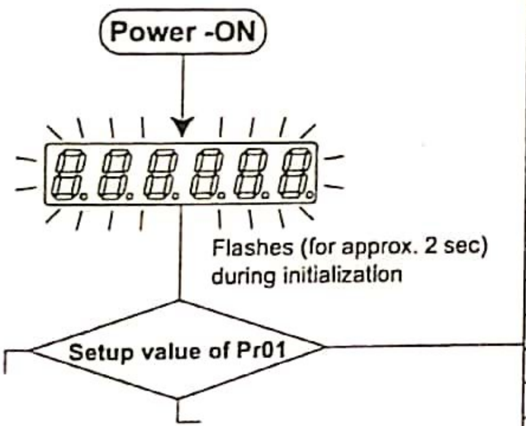
Standard default : < >

PrNo.	Title	Setup range	Function/Content
00 *	Address	0 to 15 <1>	In the communication with the host via RS232/485 for multi-axes application, it is necessary to identify which axis the host is communicating. Use this parameter to confirm the address of the axis in numbers.

- The address is determined by the setup value of rotary switch (0 to F) of the front panel at power-on.
- This value becomes the axis number at serial communication.
- The setup value of this parameter has no effect to the servo action.
- You cannot change the setup of Pr00 with other means than rotary switch.



PrNo.	Title	Setup range	Function/Content
01 *	LED initial status	0 to 17 <1>	You can select the type of data to be displayed on the front panel LED (7 segment) at the initial status after power-on.



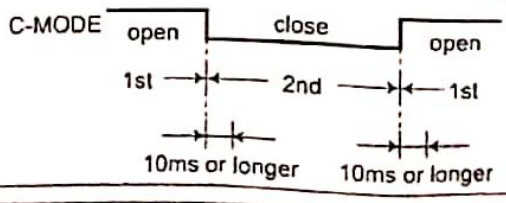
Setup value	Content
0	Positional deviation
<1>	Motor rotational speed
2	Torque output
3	Control mode
4	I/O signal status
5	Error factor/history
6	Software version
7	Alarm
8	Regenerative load factor
9	Over-load factor
10	Inertia ratio
11	Sum of feedback pulses
12	Sum of command pulses
13	External scale deviation
14	Sum of external scale feedback pulses
15	Motor automatic recognizing function
16	Analog input value
17	Factor of "No-Motor Running"

For details of display, refer to P.51 "Setup of Parameter and Mode" of Preparation.

PrNo.	Title	Setup range	Function/Content
02 *	Setup of control mode	0 to 6 <1>	You can set up the control mode to be used.

Setup value	Control mode 1st mode	Control mode 2nd mode
0	Position	–
<1>	Velocity	–
2	Torque	–
3 **1	Position	Velocity
4 **1	Position	Torque
5 **1	Velocity	Torque
6	Full-closed	–

**1) When you set up the combination mode of 3, 4 or 5, you can select either the 1st or the 2nd with control mode switching input (C-MODE).
When C-MODE is open, the 1st mode will be selected.
When C-MODE is shorted, the 2nd mode will be selected.
Don't enter commands 10ms before/after switching.

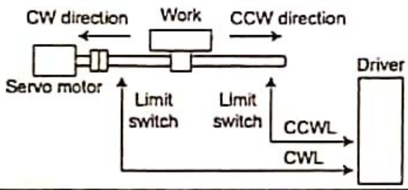


<Notes>

- For parameters which No. have a suffix of "*", changed contents will be validated when you turn on the control power.

Standard default : < >

PrNo.	Title	Setup range	Function/Content
04 *	Setup of over-travel inhibit input	0 to 2 <1>	In linear drive application, you can use this over-travel inhibiting function to inhibit the motor to run to the direction specified by limit switches which are installed at both ends of the axis, so that you can prevent the work load from damaging the machine due to the over-travel. With this input, you can set up the action of over-travel inhibit input.



Setup value	CCWL/CWL input	Input	Connection to COM–	Action
0	Valid	CCWL (CN X5,Pin-9)	Close	Normal status while CCW-side limit switch is not activated.
			Open	Inhibits CCW direction, permits CW direction.
		CWL (CN X5,Pin-9)	Close	Normal status while CW-side limit switch is not activated.
			Open	Inhibits CW direction, CCW direction permitted.
<1>	Invalid	Both CCWL and CWL inputs will be ignored, and over-travel inhibit function will be invalidated.		
2	Valid	Err38 (Over-travel inhibit input protection) is triggered when either one of the connection of CW or CCW inhibit input to COM– become open.		

<Cautions>

1. When Pr04 is set to 0 and over-travel inhibit input is entered, the motor decelerates and stops according to the preset sequence with Pr66 (Sequence at over-travel inhibition). For details, refer to the explanation of Pr66.
2. When both of CCWL and CWL inputs are opened while Pr04 is set to 0, the driver trips with Err38 (Overtravel inhibit input error) judging that this is an error.
3. When you turn off the limit switch on upper side of the work at vertical axis application, the work may repeat up/down movement because of the loosing of upward torque. In this case, set up Pr66 to 2, or limit with the host controller instead of using this function.

PrNo.	Title	Setup range	Function/Content
06	Selection of ZEROSPD input	0 to 2 <0>	You can set up the function of the speed zero clamp Input (ZEROSPD : CN X5, Pin-26)

Setup value	Function of ZEROSPD (Pin-26)
<0>, 2	ZEROSPD input is ignored and the driver judge that it Is not in speed zero clamp status.
1	ZEROSPD input becomes valid. Speed command is taken as 0 by opening the connection to COM–.

PrNo.	Title	Setup range	Function/Content
07	Selection of speed monitor (SP)	0 to 9 <3>	You can set up the content of analog speed monitor signal output (SP : CN X5, Pin43) and the relation between the output voltage level and the speed.

Setup value	Signal of SP	Relation between the output voltage level and the speed
0	Motor aclual speed	6V / 47 r/min
1		6V / 188 r/min
2		6V / 750 r/min
<3>		6V / 3000 r/min
4		1.5V / 3000 r/min
5	Command speed	6V / 47 r/min
6		6V / 188 r/min
7		6V / 750 r/min
8		6V / 3000 r/min
9		1.5V / 3000 r/min

Parameter Setup

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Function/Content</th></tr>
<tr><td>08</td><td>Selection of torque monitor (IM)</td><td>0 to 12
<0></td><td>You can set up the content of the analog torque monitor of the signal output (IM : CN X5, Pin-42), and the relation between the output voltage level and torque or deviation pulse counts.
<table>
<tr><th>Setup value</th><th>Signal of IM</th><th>Relation between the output voltage level and torque or deviation pulse counts</th></tr>
<tr><td><0></td><td>Torque command</td><td>3V/rated (100%) torque</td></tr>
<tr><td>1</td><td rowspan="5">Position deviation</td><td>3V / 31Pulse</td></tr>
<tr><td>2</td><td>3V / 125Pulse</td></tr>
<tr><td>3</td><td>3V / 500Pulse</td></tr>
<tr><td>4</td><td>3V / 2000Pulse</td></tr>
<tr><td>5</td><td>3V / 8000Pulse</td></tr>
<tr><td>6</td><td rowspan="5">Full-closed deviation</td><td>3V / 31Pulse</td></tr>
<tr><td>7</td><td>3V / 125Pulse</td></tr>
<tr><td>8</td><td>3V / 500Pulse</td></tr>
<tr><td>9</td><td>3V / 2000Pulse</td></tr>
<tr><td>10</td><td>3V / 8000Pulse</td></tr>
<tr><td>11</td><td rowspan="2">Torque command</td><td>3V / 200% torque</td></tr>
<tr><td>12</td><td>3V / 400% torque</td></tr>
</table></td></tr>
<tr><td>09</td><td>Selection of TLC output</td><td>0 to 8
<0></td><td>You can assign the function of the torque in-limit output (TLC : CN X5 Pin-40).
<table>
<tr><th>Setup value</th><th>Function</th><th>Note</th></tr>
<tr><td><0></td><td>Torque in-limit output</td><td rowspan="9">For details of function of each output of the left, refer to the table of P168, "Selection of TCL and ZSP outputs".</td></tr>
<tr><td>1</td><td>Zero speed detection output</td></tr>
<tr><td>2</td><td>Alarm output of either one of Over-regeneration /Over-load/Absolute battery/Fan lock/External scale</td></tr>
<tr><td>3</td><td>Over-regeneration alarm trigger output</td></tr>
<tr><td>4</td><td>Overload alarm output</td></tr>
<tr><td>5</td><td>Absolute battery alarm output</td></tr>
<tr><td>6</td><td>Fan lock alarm output</td></tr>
<tr><td>7</td><td>External scale alarm output</td></tr>
<tr><td>8</td><td>In-speed (Speed coincidence) output</td></tr>
</table></td></tr>
<tr><td>0A</td><td>Selection of ZSP output</td><td>0 to 8
<1></td><td>You can assign the function of the zero speed detection output (ZSP: CN X5 Pin-12).
<table>
<tr><th>Setup value</th><th>Function</th><th>Note</th></tr>
<tr><td>0</td><td>Torque in-limit output</td><td rowspan="9">For details of function of each output of the left, refer to the table of P.168, "Selection of TCL and ZSP outputs".</td></tr>
<tr><td><1></td><td>Zero speed detection output</td></tr>
<tr><td>2</td><td>Alarm output of either one of Over-regeneration /Over-load/Absolute battery/Fan lock/External scale</td></tr>
<tr><td>3</td><td>Over-regeneration alarm trigger output</td></tr>
<tr><td>4</td><td>Overload alarm output</td></tr>
<tr><td>5</td><td>Absolute battery alarm output</td></tr>
<tr><td>6</td><td>Fan lock alarm output</td></tr>
<tr><td>7</td><td>External scale alarm output</td></tr>
<tr><td>8</td><td>In-speed (Speed coincidence) output</td></tr>
</table></td></tr>
<tr><td>0B
*</td><td>Setup of absolute encoder</td><td>0 to 2
<1></td><td>You can set up the using method of 17-bit absolute encoder.
<table>
<tr><th>Setup value</th><th>Content</th></tr>
<tr><td>0</td><td>Use as an absolute encoder.</td></tr>
<tr><td><1></td><td>Use as an incremental encoder.</td></tr>
<tr><td>2</td><td>Use as an absolute encoder, but ignore the multi-turn counter over.</td></tr>
</table>
<Caution>
This parameter will be invalidated when 5-wire, 2500P/r incremental encoder is used.</td></tr>
<tr><td>0C
*</td><td>Baud rate setup of RS232 communication</td><td>0 to 5
<2></td><td>You can set up the communication speed of RS232. • Error of baud rate is ±0.5%.
<table>
<tr><th>Setup value</th><th>Baud rate</th><th>Setup value</th><th>Baud rate</th></tr>
<tr><td>0</td><td>2400bps</td><td>3</td><td>19200bps</td></tr>
<tr><td>1</td><td>4800bps</td><td>4</td><td>38400bps</td></tr>
<tr><td><2></td><td>9600bps</td><td>5</td><td>57600bps</td></tr>
</table></td></tr>
</table>

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Function/Content</th></tr>
<tr><td>0D
*</td><td>Baud rate setup of RS485 communication</td><td>0 to 5
<2></td><td>You can set up the communication speed of RS485.
• Error of baud rate is ±0.5%.
<table><tr><th>Setup value</th><th>Baud rate</th></tr><tr><td>0</td><td>2400bps</td></tr><tr><td>1</td><td>4800bps</td></tr><tr><td><2></td><td>9600bps</td></tr></table><table><tr><th>Setup value</th><th>Baud rate</th></tr><tr><td>3</td><td>19200bps</td></tr><tr><td>4</td><td>38400bps</td></tr><tr><td>5</td><td>57600bps</td></tr></table></td></tr>
<tr><td>0E
*</td><td>Setup of front panel lock</td><td>0 to 1
<0></td><td>You can limit the operation of the front panel to the monitor mode only.
You can prevent such a misoperation as unexpected parameter change.
<table><tr><th>Setup value</th><th>Content</th></tr><tr><td><0></td><td>Valid to all</td></tr><tr><td>1</td><td>Monitor mode only</td></tr></table><Note>
You can still change parameters via communication even though this setup is 1.
To return this parameter to 0, use the console or the "PANATERM®".</td></tr>
</table>

Parameters for Adjustment of Time Constants of Gains and Filters

Standard default : < >

PrNo.	Title	Setup range	Unit	Function/Content
11	1st gain of velocity loop	1 to 3500 A to C-frame:<35>* D to F-frame:<18>*	Hz	You can determine the response of the velocity loop. In order to increase the response of overall servo system by setting high position loop gain, you need higher setup of this velocity loop gain as well. However, too high setup may cause oscillation. <Caution> When the inertia ratio of Pr20 is set correctly, the setup unit of Pr11 becomes (Hz).
12	1st time constant of velocity loop integration	1 to 1000 A to C-frame:<16>* D to F-frame:<31>*	ms	You can set up the integration time constant of velocity loop. Smaller the setup, faster you can dog-in deviation at stall to 0. The integration will be maintained by setting to "999". The integration effect will be lost by setting to "1000".
13	1st filter of speed detection	0 to 5 <0>*	–	You can set up the time constant of the low pass filter (LPF) after the speed detection, in 6 steps. Higher the setup, larger the time constant you can obtain so that you can decrease the motor noise, however, response becomes slow. Use with a default value of 0 in normal operation.
14	1st time constant of torque filter	0 to 2500 A to C-frame:<65>* D to F-frame:<126>*	0.01ms	You can set up the time constant of the 1st delay filter inserted in the torque command portion. You might expect suppression of oscillation caused by distortion resonance.
19	2nd gain of velocity loop	1 to 3500 A to C-frame:<35>* D to F-frame:<18>*	Hz	Position loop, velocity loop, speed detection filter and torque command filter have their 2 pairs of gain or time constant (1st and 2nd). For details of switching the 1st and the 2nd gain or the time constant, refer to P.226, "Adjustment". The function and the content of each parameter is as same as that of the 1st gain and time constant.
1A	2nd time constant of velocity loop integration	1 to 1000 <1000>*	ms	
1B	2nd filter of velocity detection	0 to 5 <0>*	–	
1C	2nd time constant of torque filter	0 to 2500 A to C-frame:<65>* D to F-frame:<126>*	0.01ms	
1D	1st notch frequency	100 to 1500 <1500>	Hz	You can set up the frequency of the 1st resonance suppressing notch filter. The notch filter function will be invalidated by setting up this parameter to "1500".

<Notes>

- For parameters which No. have a suffix of "*", changed contents will be validated when you turn on the control power.
- Parameters which default values have a suffix of "*" will be automatically set up during real time auto-gain tuning. When you change manually, invalidate the real-time auto-gain tuning first then set, referring to P.239, "Release of Automatic Gain Adjusting Function" of Adjustment.

Connection and Setup of Torque Control Mode

Standard default : < >

PrNo.	Title	Setup range	Unit	Function/Content
1E	1st notch width selection	0 to 4 <2>	–	You can set up the notch filter width of the 1st resonance suppressing filter in 5 steps. Higher the setup, larger the notch width you can obtain. Use with default setup in normal operation.

Parameters for Auto-Gain Tuning

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>20</td><td>Inertia ratio</td><td>0 to 10000
<250>*</td><td>%</td><td>You can set up the ratio of the load inertia against the rotor (of the motor) inertia.

Pr20=(load inertia/rotor inertia) X 100 [%]

When you execute the normal auto-gain tuning, the load inertial will be automatically estimated after the preset action, and this result will be reflected in this parameter.
The inertia ratio will be estimated at all time while the real-tiem auto-gain tuning is valid, and its result will be saved to EEPROM every 30 min.
<Caution>
If the inertia ratio is correctly set, the setup unit of Pr11 and Pr19 becomes (Hz). When the inertia ratio of Pr20 is larger than the actual, the setup unit of the velocity loop gain becomes larger, and when the inertia ratio of Pr20 is smaller than the actual, the setup unit of the velocity loop gain becomes smaller.</td></tr>
<tr><td>21</td><td>Setup of real-time auto-gain tuning</td><td>0 to 7
<1></td><td>–</td><td>You can set up the action mode of the real-time auto-gain tuning.
With higher setup such as 3, the driver respond quickly to the change of the inertia during operation, however it might cause an unstable operation. Use 1for normal operation.
<table>
<tr><th>Setup value</th><th>Real-time auto-gain tuning</th><th>Varying degree of load inertia in motion</th></tr>
<tr><td>0</td><td>Invalid</td><td>–</td></tr>
<tr><td><1>, 4, 7</td><td rowspan="3">Normal mode</td><td>Little change</td></tr>
<tr><td>2, 5</td><td>Gradual change</td></tr>
<tr><td>3, 6</td><td>Rapid change</td></tr>
</table>
</td></tr>
<tr><td>22</td><td>Selection of machine stiffness at real-time auto-gain tuning</td><td>0 to 15
A to C-frame:
<4>
D to F-frame:
<1></td><td>–</td><td>You can set up the machine stiffness in 16 steps while the real-time auto-gain tuning is valid.

low←machine stiffness→high
low← servo gain →high
Pr22 | 0, 1- - - - - - - - - - - - 14, 15
low← response →high

<Caution>
When you change the setup value rapidly, the gain changes rapidly as well, and this may give impact to the machine. Increase the setup gradually watching the movement of the machine.</td></tr>
</table>

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>25</td><td>Setup of an action at normal mode auto-gain tuning</td><td>0 to 7
<0></td><td>–</td><td>You can set up the action pattern at the normal mode auto-gain tuning.
<table>
<tr><th>Setup value</th><th>Number of revolution</th><th>Rotational direction</th></tr>
<tr><td><0></td><td rowspan="4">2 [revolution]</td><td>CCW → CW</td></tr>
<tr><td>1</td><td>CW → CCW</td></tr>
<tr><td>2</td><td>CCW → CCW</td></tr>
<tr><td>3</td><td>CW → CW</td></tr>
<tr><td>4</td><td rowspan="4">1 [revolution]</td><td>CCW → CW</td></tr>
<tr><td>5</td><td>CW → CCW</td></tr>
<tr><td>6</td><td>CCW → CCW</td></tr>
<tr><td>7</td><td>CW → CW</td></tr>
</table>
e.g.) When the setup is 0, the motor turns 2 revolutions to CCW and 2 revolutions to CW.</td></tr>
<tr><td>28</td><td>2nd notch frequency</td><td>100 to 1500
<1500></td><td>Hz</td><td>You can set up the 2nd notch width of the resonance suppressing filter in 5 steps. The notch filter function is invalidated by setting up this parameter to "1500".</td></tr>
<tr><td>29</td><td>Selection of 2nd notch width</td><td>0 to 4
<2></td><td>–</td><td>You can set up the notch width of 2nd resonance suppressing filter in 5 steps. Higher the setup, larger the notch width you can obtain.
Use with default setup in normal operation.</td></tr>
<tr><td>2A</td><td>Selection of 2nd notch depth</td><td>0 to 99
<0></td><td>–</td><td>You can set up the 2nd notch depth of the resonance suppressing filter. Higher the setup, shallower the notch depth and smaller the phase delay you can obtain.</td></tr>
</table>

Parameters for Adjustment (2nd Gain Switching Function)

Standard default : < >

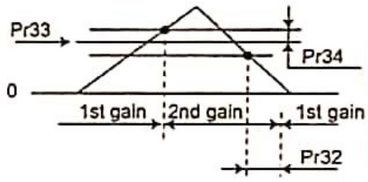
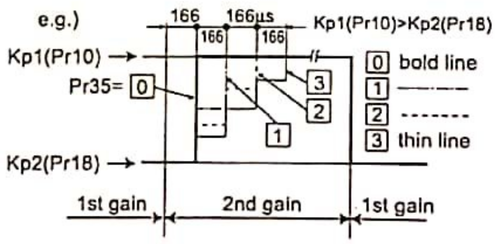
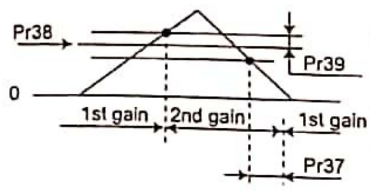
<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>30</td><td>Setup of 2nd gain</td><td>0 to 1
<1>*</td><td>–</td><td>You can select the PI/P action switching of the velocity control or 1st/2nd gain switching.
<table>
<tr><th>Setup value</th><th>Gain selection/switching</th></tr>
<tr><td>0</td><td>1st gain (PI/P switching enabled) *1</td></tr>
<tr><td><1>*</td><td>1st/2nd gain switching enabled *2</td></tr>
</table>
*1 Switch the PI/P action with the gain switching input (GAIN CN X5, Pin-27). PI is fixed when Pr03 (Torque limit selection) is 3.
<table>
<tr><th>GAIN input</th><th>Action of velocity loop</th></tr>
<tr><td>Open with COM–</td><td>PI action</td></tr>
<tr><td>Connect to COM–</td><td>P action</td></tr>
</table>
*2 For switching condition of the 1st and the 2nd, refer to P.243, "Gain Switching Function" of Adjustment.</td></tr>
<tr><td>31</td><td>1st mode of control switching</td><td>0 to 10
<0>*</td><td>–</td><td>You can select the switching condition of 1st gain and 2nd gain while Pr30 is set to 1.</td></tr>
<tr><td colspan="5">
<table>
<tr><th>Setup value</th><th></th><th>Gain switching condition</th></tr>
<tr><td><0>*, 4 to 10</td><td></td><td>Fixed to the 1st gain.</td></tr>
<tr><td>1</td><td></td><td>Fixed to the 2nd gain.</td></tr>
<tr><td>2</td><td>*1</td><td>2nd gain selection when the gain switching input is turned on. (Pr30 setup must be 1.)</td></tr>
<tr><td>3</td><td>*2</td><td>2nd gain selection when the toque command variation is larger than the setups of Pr33 (1st level of control switching) and Pr34 (1st hysteresis of control switching).</td></tr>
</table>
</td></tr>
<tr><td></td><td></td><td></td><td></td><td>*1 Fixed to the 1st gain regardless of GAIN input, when Pr31 is set to 2 and Pr03 (Torque limit selection) is set to 3.
*2 For the switching level and the timing, refer to P.243, "Gain Switching Function" of Adjustment.</td></tr>
</table>

<Notes>

- Parameters which default values have a suffix of "*" will be automatically set up during real time auto-gain tuning. When you change manually, invalidate the real-time auto-gain tuning first then set, referring to P.239, "Release of Automatic Gain Adjusting Function" of Adjustment.

Parameter Setup

Standard default : < >

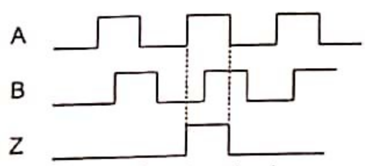
PrNo.	Title	Setup range	Unit	Function/Content
32	1st delay time of control switching	0 to 10000 <30>*	x 166µs	You can set up the delay time when returning from the 2nd to the 1st gain, while Pr31 is set to 3.
33	1st level of control switching	0 to 20000 <50>*	–	You can set up the switching (judging) level of the 1st and the 2nd gains, while Pr31 is set to 3. Unit varies depending on the setup of Pr31 (1st mode of control switching)
34	1st hysteresis of control switching	0 to 20000 <33>*	–	You can set up hysteresis width to be implemented above/below the judging level which is set up with Pr33. Unit varies depending on the setup of Pr31 (1st control switching mode). Definitions of Pr32 (Delay), Pr33 (Level) and Pr34 (Hysteresis) are explained in the fig. below.  **<Caution>** The setup of Pr33 (Level) and Pr34 (Hysteresis) are valid as absolute values (positive/negative).
35	Switching time of position gain	0 to 10000 <20>*	(setup value +1) x 166µs	You can setup the step-by-step switching time to the position loop gain only at gain switching while the 1st and the 2nd gain switching is valid.  **<Caution>** The switching time is only valid when switching from small position gain to large position gain.
37	2nd delay time of control switching	0 to 10000 <0>	x 166µs	You can set up the delay time when returning from 2nd to 1st gain, while Pr36 is set to 3 to 5.
38	2nd level of control switching	0 to 20000 <0>	–	You can set up the switching (judging) level of the 1st and the 2nd gains, while Pr36 is set to 3 to 5 Unit varies depending on the setup of Pr36 (2nd mode of control switching).
39	2nd hysteresis of control switching	0 to 20000 <0>	–	You can set up the hysteresis width to be implemented above/below the judging level which is set up with Pr38. Unit varies depending on the setup of Pr36 (2nd mode of control switching).Definition of Pr37 (Delay), Pr38 (Level) and Pr39 (Hysteresis) are explained in the fig. below.  **<Caution>** Setup of Pr38 (Level) and Pr39 (Hysteresis) are valid as absolute value (positive/negative).
3D	JOG speed setup	0 to 500 <300>	r/min	You can setup the JOG speed. Refer to P.75, "Trial Run"of Preparation.

Parameters for Position Control

Standard default : < >

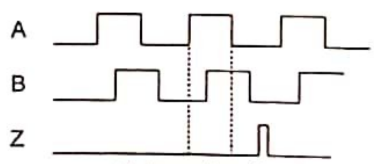
PrNo.	Title	Setup range	Function/Content
44 *	Numerator of pulse output division	1 to 32767 <2500>	You can set up the pulse counts to be fed out from the pulse output (X5 0A+ : Pin-21, 0A- : Pin-22, 0B+ : Pin-48, 0B- : Pin-49). **• Pr45=<0> (Default)** You can set up the output pulse counts per one motor revolution for each OA and OB with the Pr44 setup. Therefore the pulse output resolution after quadruple can be obtained from the formula below. The pulse output resolution per one revolution = Pr44 (Numerator of pulse output division) X4 **• Pr45≠0 :** The pulse output resolution per one revolution can be divided by any ration according to the formula below. Pulse output resolution per one revolution $\frac{\text{Pr44 (Numerator of pulse output division)}}{\text{Pr45 (Denominator of pulse output division)}}$ x Encoder resolution **<Cautions>** • The encoder resolution is 131072 [P/r] for the 17-bit absolute encoder, and 10000 [P/r] for the 5-wire 2500P/r incremental encoder. • The pulse output resolution per one revolution cannot be greater than the encoder resolution. (In the above setup, the pulse output resolution equals to the encoder resolution.) • Z-phase is fed out once per one revolution of the motor. When the pulse output resolution obtained from the above formula is multiple of 4, Z-phase synchronizes with A-phase. In other case, the Z-phase width equals to output with the encoder resolution, and becomes narrower than A-phase, hence does not synchronize with A-phase.
45 *	Deniminator of pulse output division	0 to 32767 <0>	

when encoder resolution x $\frac{Pr44}{Pr45}$ is multiple of 4



Synchronized

when encoder resolution x $\frac{Pr44}{Pr45}$ is not multiple of 4



Not-synchronized

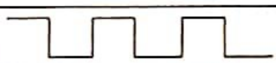
<Notes>

- For parameters which No. have a suffix of "*", changed contents will be validated when you turn on the control power.
- Parameters which default values have a suffix of "*" will be automatically set up during real time auto-gain tuning. When you change manually, invalidate the real-time auto-gain tuning first then set, referring to P.239, "Release of Automatic Gain Adjusting Function" of Adjustment.

Parameter Setup

Standard default : < >

PrNo.	Title	Setup range	Function/Content
46 *	Reversal of pulse output logic	0 to 3 <0>	You can set up the B-phase logic and the output source of the pulse output (X5 OB+ : Pin-48, OB– : Pin-49). With this parameter, you can reverse the phase relation between the A-phase pulse and the B-phase pulse by reversing the B-phase logic.

Setup value	A-phase (OA)	at motor CCW rotation	at motor CW rotation
			
<0>, 2	B-phase(OB) non-reversal		
1, 3	B-phase(OB) reversal		

Pr46	B-phase logic	Output source
<0>	Non-reversal	Encoder position
1	Reversal	Encoder position
2 *1	Non-reversal	External scale position
3 *1	Reversal	External scale position

*1 The output source of Pr46=2, 3 is valid onlt at full-closed control.

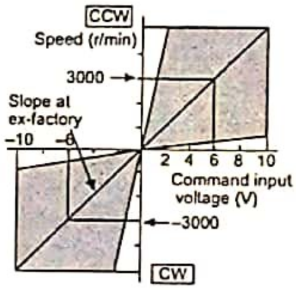
<Notes>

- For parameters which No. have a suffix of "*", changed contents will be validated when you turn on the control power.

Parameters for Velocity and Torque Control

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>50</td><td>Input gain of speed command</td><td>10 to 2000
<500></td><td>(r/min)/V</td><td>You can set up the relation between the voltage applied to the speed command input (SPR : CN X5, Pin-14) and the motor speed.

• You can set up a "slope" of the relation between the command input voltage and the motor speed, with Pr50.
• Default is set to Pr50=500 [r/min], hence input of 6V becomes 3000r/min.


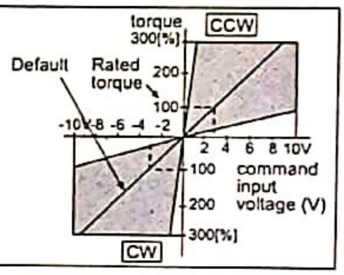
<Cautions>
1. Do not apply more than ±10V to the speed command input (SPR).
2. When you compose a position loop outside of the driver while you use the driver in velocity control mode, the setup of Pr50 gives larger variance to the overall servo system.
Pay an extra attention to oscillation caused by larger setup of Pr50.</td></tr>
<tr><td>52</td><td>Speed command offset</td><td>–2047 to 2047
<0></td><td>0.3mV</td><td>• You can make an offset adjustment of analog speed command (SPR : CN X5, Pin-14) with this parameter.
• The offset volume is 0.3mV per setup value of "1".
• There are 2 offset methods, (1) Manual adjustment and (2) Automatic adjustment.

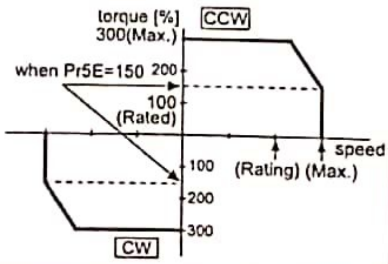
1) Manual adjustment
• When you make an offset adjustment with the driver alone, Enter 0 V exactly to the speed command input (SPR/TRQR), (or connect to the signal ground), then set this parameter up so that the motor may not turn.
• when you compose a position loop with the host,
• Set this parameter up so that the deviation pulse may be reduced to 0 at the Servo-Lock status.
2) Automatic adjustment
• For the details of operation method at automatic offset adjustment mode, refer to P.73, "Auxiliary Function Mode" of Preparation.
• Result after the execution of the automatic offset function will be reflected in this parameter, Pr52.</td></tr>
<tr><td>56</td><td>4th speed of speed setup</td><td>–20000 to 20000
<0></td><td>r/min</td><td>You can set up the speed limit value in unit of [r/min].
<Caution>
The absolute value of the parameter setup is limited by Pr73 (Set up of over-speed level).</td></tr>
<tr><td>57</td><td>Setup of speed command filter</td><td>0 to 6400
<0></td><td>10µs</td><td>You can set up the time constant of the primary delay filter to the analog speed command/analog torque command/analog velocity control (SPR : CN X5, Pin-14)</td></tr>
<tr><td>5B</td><td>Selection of torque command</td><td>0 to 1
<0></td><td>–</td><td>You can select the input of the torque command and the speed limit.
<table><tr><th>Pr5B</th><th>Torque command</th><th>Velocity limit</th></tr><tr><td><0></td><td>SPR/TRQR/SPL</td><td>Pr56</td></tr><tr><td>1</td><td>CCWTL/TRQR</td><td>SPR/TRQR/SPL</td></tr></table></td></tr>
</table>

Parameter Setup

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>5C</td><td>Input gain of torque command</td><td>10 to 100
<30></td><td>0.1V/
100%</td><td>You can set the relation between the voltage applied to the torque command input (SPR/TRQR : CN X5, Pin-14 or CCWTL/TRQR : CN X5, Pin-16) and the motor output torque.

• Unit of the setup value is [0.1V/100%] and set up input voltage necessary to produce the rated torque.
• Default setup of 30 represents 3V/100%.

</td></tr>
<tr><td>5D</td><td>Input reversal of torque command</td><td>0 to 1
<0></td><td>–</td><td>You can reverse the polarity of the torque command input (SPR/TRQR : CN X5, Pin-14 or CCWTL/TRQR : CN X5, Pin-16)
<table><tr><th>Setup value</th><th>Direction of motor output torque</th></tr><tr><td><0></td><td>CCW direction (viewed from motor shaft) with (+) command</td></tr><tr><td>1</td><td>CW direction (viewed from motor shaft) with (+) command</td></tr></table></td></tr>
<tr><td>5E</td><td>1st torque limit setup</td><td>0 to 500
<500>
*2</td><td>%</td><td>You can limit the max torque for both CCW and CW direction with Pr5E. Pr03 setup and Pr5F are ignored.

This torque limit function limits the max. motor torque with the parameter setup.
In normal operation, this driver permits approx. 3 times larger torque than the rated torque instantaneously. If this 3 times bigger torque causes any trouble to the load (machine) strength, you can use this function to limit the max. torque.
• Setup value is to be given in % against the rated torque.
• Right fig. shows example of 150% setup with Pr03=1.
• Pr5E limits the max. torque for both CCW and CW directions.


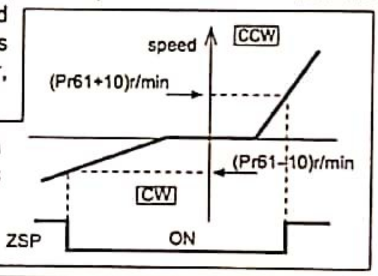
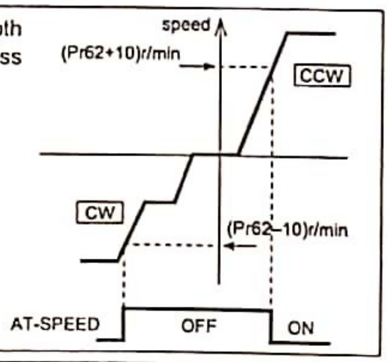
<Caution>
You cannot set up a larger value to this parameter than the default setup value of "Max. output torque setup" of System parameter (which you cannot change through operation with PANATERM® or panel). Default value varies depending on the combination of the motor and the driver. For details, refer to P.57, "Setup of Torque Limit " of Preparation.</td></tr>
</table>

<Notes>

• For parameters which default. has a suffix of "*2", value varies depending on the combination of the driver and the motor.

Parameters for Sequence

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>61</td><td>Zero-speed</td><td>10 to
20000
<50></td><td>r/min</td><td>You can set up the timing to feed out the zero-speed detection output signal (ZSP : CN X5, Pin-12 or TCL : CN X5, Pin-40) in rotational speed [r/min].
The zero-speed detection signal (ZSP) will be fed out when the motor speed falls below the setup of this parameter, Pr61.
In-speed (Speed coincidence) signal (V-COIN) will be fed out when the difference between the speed command and the motor speed falls below the setup of this parameter, Pr61.
• The setup of P61 is valid for both CCW and CW direction regardless of the motor rotating direction.
• There is hysteresis of 10 [r/min].

</td></tr>
<tr><td>62</td><td>At-speed
(Speed arrival)</td><td>10 to
20000
<50></td><td>r/min</td><td>You can set up the timing to feed out the At-speed signal (COIN+ : CN X5, Pin-39, COIN- : CN X5, Pin-38)
At-speed (Speed arrival) (COIN) will be fed out when the motor speed exceeds the setup speed of this parameter, Pr62
• The setup of P62 is valid for both CCW and CW direction regardless of the motor rotational direction.
• There is hysteresis of 10 [r/min].

</td></tr>
<tr><td>65</td><td>LV trip selection at main power OFF</td><td>0 to 1
<1></td><td>–</td><td>You can select whether or not to activate Err13 (Main power under-voltage protection) function while the main power shutoff continues for the setup of Pr6D (Main power-OFF detection time).
<table><tr><th>Setup value</th><th>Action of main power low voltage protection</th></tr><tr><td>0</td><td>When the main power is shut off during Servo-ON, Err13 will not be triggered and the driver turns to Servo-OFF. The driver returns to Servo-ON again after the main power resumption.</td></tr><tr><td><1></td><td>When the main power is shut off during Servo-ON, the driver will trip due to Err13 (Main power low voltage protection).</td></tr></table>
<Caution>
This parameter is invalid when Pr6D (Detection time of main power OFF)=1000. Err13 (Main power under-voltage protection) is triggered when setup of P66D is long and P-N voltage of the main converter falls below the specified value before detecting the main power shutoff, regardless of the Pr65 setup. Refer to P.42, "Timing Chart-At Power-ON" of Preparation as well.</td></tr>
</table>

Parameter Setup

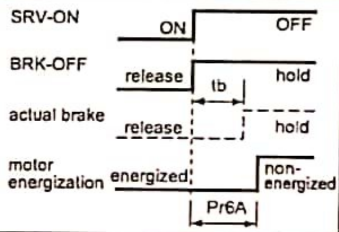
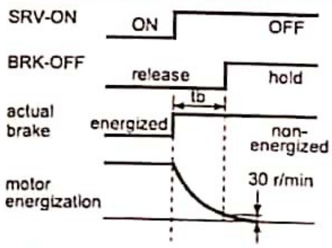
Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>66
*</td><td>Sequence at over-travel inhibit</td><td>0 to 2
<0></td><td>–</td><td>You can set up the running condition during deceleration or after stalling, while over-travel inhibit input (CCWL : Connector CN X5, Pin-9 or CWL : Connector CN X5, Pin-8) is valid
<table>
<tr><th>Setup value</th><th>During deceleration</th><th>After stalling</th><th>Deviation counter content</th></tr>
<tr><td><0></td><td>Dynamic brake action</td><td>Torque command=0 towards inhibited direction</td><td>Hold</td></tr>
<tr><td>1</td><td>Torque command=0 towards inhibited direction</td><td>Torque command=0 towards inhibited direction</td><td>Hold</td></tr>
<tr><td>2</td><td>Emergency stop</td><td>Torque command=0 towards inhibited direction</td><td>Clears before/ after deceleration</td></tr>
</table>
<Caution>
In case of the setup value of 2, torque limit during deceleration will be limited by the setup value of Pr6E (Torque setup at emergency stop).</td></tr>
<tr><td>67</td><td>Sequence at main power OFF</td><td>0 to 9
<0></td><td>–</td><td>When Pr65 (LV trip selection at main power OFF) is 0, you can set up,
1) the action during deceleration and after stalling
2) the clearing of deviation counter content
after the main power is shut off.
<table>
<tr><th rowspan="2">Setup value</th><th colspan="2">Action</th><th rowspan="2">Deviation counter content</th></tr>
<tr><th>During deceleration</th><th>After stalling</th></tr>
<tr><td><0></td><td>DB</td><td>DB</td><td>Clear</td></tr>
<tr><td>1</td><td>Free-run</td><td>DB</td><td>Clear</td></tr>
<tr><td>2</td><td>DB</td><td>Free-run</td><td>Clear</td></tr>
<tr><td>3</td><td>Free-run</td><td>Free-run</td><td>Clear</td></tr>
<tr><td>4</td><td>DB</td><td>DB</td><td>Hold</td></tr>
<tr><td>5</td><td>Free-run</td><td>DB</td><td>Hold</td></tr>
<tr><td>6</td><td>DB</td><td>Free-run</td><td>Hold</td></tr>
<tr><td>7</td><td>Free-run</td><td>Free-run</td><td>Hold</td></tr>
<tr><td>8</td><td>Emergency stop</td><td>DB</td><td>Clear</td></tr>
<tr><td>9</td><td>Emergency stop</td><td>Free-run</td><td>Clear</td></tr>
</table>
(DB: Dynamic Brake action)
<Caution>
In case of the setup value of 8 or 9, torque limit during deceleration will be limited by the setup value of Pr6E (Torque setup at emergency stop).</td></tr>
<tr><td>68</td><td>Sequence at alarm</td><td>0 to 3
<0></td><td>–</td><td>You can set up the action during deceleration or after stalling when some error occurs while either one of the protective functions of the driver is triggered.
<table>
<tr><th rowspan="2">Setup value</th><th colspan="2">Action</th><th rowspan="2">Deviation counter content</th></tr>
<tr><th>During deceleration</th><th>After stalling</th></tr>
<tr><td><0></td><td>DB</td><td>DB</td><td>Hold</td></tr>
<tr><td>1</td><td>Free-run</td><td>DB</td><td>Hold</td></tr>
<tr><td>2</td><td>DB</td><td>Free-run</td><td>Hold</td></tr>
<tr><td>3</td><td>Free-run</td><td>Free-run</td><td>Hold</td></tr>
</table>
(DB: Dynamic Brake action)
<Caution>
The content of the deviation counter will be cleared when clearing the alarm. Refer to P.43, "Timing Chart (When an error (alarm) occurs (at Servo-ON command status)" of Preparation.</td></tr>
</table>

<Notes>

• For parameters which No. have a suffix of "*", changed contents will be validated when you turn on the control power.

Standard default : < >

PrNo.	Title	Setup range	Unit	Function/Content
69	Sequence at Servo-Off	0 to 9 <0>	–	You can set up, 1) the action during deceleration and after stalling 2) the clearing of deviation counter content, after turning to Servo-OFF (SRV-ON signal : CN X5, Pin-29 is turned from ON to OFF) The relation between the setup value of Pr69 and the action/deviation counter clearance is same as that of Pr67 (Sequence at Main Power Off) Refer to P.44, "Timing Chart"-Servo-ON/OFF action while the motor is at stall" of Preparation as well.
6A	Setup of mechanical brake action at stalling	0 to 100 <0>	2ms	You can set up the time from when the brake release signal (BRK-OFF : CN X5, Pin-10 and 11) turns off to when the motor is de-energized (Servo-free), when the motor turns to Servo-OFF while the motor is at stall. • Set up to prevent a micro-travel/ drop of the motor (work) due to the action delay time (tb) of the brake • $\boxed{\text{After setting up Pr6a} \geqq \text{tb}}$, then compose the sequence so as the driver turns to Servo-OFF after the brake is actually activated.  Refer to P.44, "Timing Chart"-Servo-ON/OFF Action While the Motor Is at Stall" of Preparation as well.
6B	Setup of mechanical brake action at running	0 to 100 <0>	2ms	You can set up time from when detecting the off of Servo-ON input signal (SRV-ON : CN X5, Pin-29) is to when external brake release signal (BRK-OFF : CN X5, Pin-10 and 11) turns off, while the motor turns to servo off during the motor in motion. • Set up to prevent the brake deterioration due to the motor running. • At Servo-OFF during the motor is running, tb of the right fig. will be a shorter one of either Pr6B setup time, or time lapse till the motor speed falls below 30r/min.  Refer to P.45, "Timing Chart"-Servo-ON/OFF action while the motor is in motion" of Preparation as well.

Parameter Setup

Standard default : < >

<table>
<tr><th>PrNo.</th><th>Title</th><th>Setup range</th><th>Unit</th><th>Function/Content</th></tr>
<tr><td>6C
*</td><td>Selection of external regenerative resistor</td><td>0 to 3
for
A, B-frame
<3>
for
C to F-frame
<0></td><td>–</td><td>With this parameter, you can select either to use the built-in regenerative resistor of the driver, or to separate this built-in regenerative resistor and externally install the regenerative resistor (between RB1 and RB2 of Connector CN X2 in case of A to D-frame, between P and B2 of terminal block in case of E, F-frame).
<table>
<tr><th>Setup value</th><th>Regenerative resistor to be used</th><th>Regenerative processing and regenerative resistor overload</th></tr>
<tr><td><0>
(C, D, E and F-frame)</td><td>Built-in resistor</td><td>Regenerative processing circuit will be activated and regenerative resistor overload protection will be triggered according to the built-in resistor (approx. 1% duty).</td></tr>
<tr><td>1</td><td>External resistor</td><td>The driver trips due to regenerative overload protection (Err18), when regenerative processing circuit is activated and its active ratio exceeds 10%.</td></tr>
<tr><td>2</td><td>External resistor</td><td>Regenerative processing circuit is activated, but no regenerative over-load protection is triggered.</td></tr>
<tr><td><3>
(A, B-frame)</td><td>No resistor</td><td>Both regenerative processing circuit and regenerative protection are not activated, and built-in capacitor handles all regenerative power.</td></tr>
</table>
<Remarks>
Install an external protection such as thermal fuse when you use the external regenerative resistor.
Otherwise, the regenerative resistor might be heated up abnormally and result in burnout, regardless of validation or invalidation of regenerative ove-rload protection.
<Caution>
When you use the built-in regenerative resistor, never to set up other value than 0. Don't touch the external regenerative resistor.
External regenerative resistor gets very hot, and might cause burning.</td></tr>
<tr><td>6D
*</td><td>Detection time of main power off</td><td>35 to 1000
<35></td><td>2ms</td><td>You can set up the time to detect the shutoff while the main power is kept shut off continuously.
The main power off detection is invalid when you set up this to 1000.</td></tr>
<tr><td>6E</td><td>Torque setup at emergency stop</td><td>0 to 500
<0></td><td>%</td><td>You can set up the torque limit in case of emergency stop as below.
• During deceleration of over-travel inhibit with the setup 2 of Pr66 (Sequence at over-travel inhibit input)
• During deceleration with the setup of 8 or 9 of Pr67 (Sequence at main power off)
• During deceleration with the setup of 8 or 9 of Pr69 (Sequence at Servo-OFF)
Normal torque limit is used by setting this to 0.</td></tr>
<tr><td>71</td><td>Setup of analog input excess</td><td>0 to 100
<0></td><td>0.1V</td><td>• You can set up the excess detection judgment level of analog velocity command (SPR : CN X5, Pin-14) with voltage after offset correction.
• Err39 (Analog input excess protective function) becomes invalid when you set up this to 0.</td></tr>
<tr><td>72</td><td>Setup of over-load level</td><td>0 to 500
<0></td><td>%</td><td>• You can set up the over-load level. The overload level becomes 115 [%] by setting up this to 0.
• Use this with 0 setup in normal operation. Set up other value only when you need to lower the over-load level.
• The setup value of this parameter is limited by 115[%] of the motor rating.</td></tr>
<tr><td>73</td><td>Setup of over-speed level</td><td>0 to 20000
<0></td><td>r/min</td><td>• You can set up the over-speed level. The over-speed level becomes 1.2 times of the motor max. speed by setting up this to 0.
• Use this with 0 setup in normal operation. Set up other value only when you need to lower the over-speed level
• The setup value of this parameter is limited by 1.2 times of the motor max. speed.
<Caution>
The detection error against the setup value is ±3 [r/min] in case of the 7-wire absolute encoder, and ±36 [r/min] in case of the 5-wire incremental encoder.</td></tr>
</table>

<Notes>

• For parameters which No. have a suffix of "*", changed contents will be validated when you turn on the control power.

Appendix B

Ultrasonic displacement sensor.

ToughSonic®/PC Distance Sensor

Computer and Teach Setup, Waterproof, Multiple Output

TSPC-30S Series

Up to 14-ft. (4.3 m) maximum range in IP68 rated 30 mm threaded housing

PC Configured Non-Contact Ultrasonic Distance Measurement

TSPC sensors and SenixVIEW software put the power of ultrasonics in your hands yet retain the simplicity of push-button TEACH setup. You can quickly adjust, optimize, save and clone your applications quickly without calibration!

ToughSonic sensors contain a rugged transducer in a stainless steel sealed housing for long life.

Outputs are proportional or controlled by measured distance. Damage is eliminated because nothing touches your materials.

Numerous applications exist in all industries. Contact Senix today to discuss your specific needs.

Features

Distance Measurements

- Long range, short dead band
- Unaffected by optical factors like color and transparency
- PC or button "teachable" setup
- Narrow beam with adjustments to optimize performance
- Temperature compensated

Packaging & Performance

- Quick bolt-in mounting
- Durable sealed housing for wet or dirty applications
- Short & overload protected I/O
- Multi-sensor synchronization
- Adjustable sensitivity
- Rear status indicators (3)

Create "Mini" Systems

With user-adjustable interface features like switch hysteresis and time delays you can create complete systems such as pump controllers or material flow controls. Save cost by eliminating separate controllers, delay circuits and time delay relays!

PC Setup Power!

Use SenixVIEW software (see separate data sheet) to select and adjust all interfaces, timing parameters, filters and modes. Then view, analyze or log data to optimize your application.

Several push-button "teach" features also provide common adjustments without the PC.

Stock, repairs, OEMs

Flexible configuration means fewer parts to stock and quick duplication! Higher volume OEM options are available.

Output Selection

In addition to the model's serial data interface there are two SenixVIEW controlled output wires. Analog and switch output selections are available to suit your application. All outputs have SenixVIEW configured features including distance, initial and no-target response, and time delays.

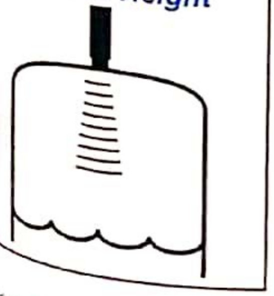
Voltage & Current Loop

Select voltage, current or both in standard (0-10 VDC, 4-20 mA) or custom ranges. The outputs are fully configurable. The analog slope may be positive or negative with distance.

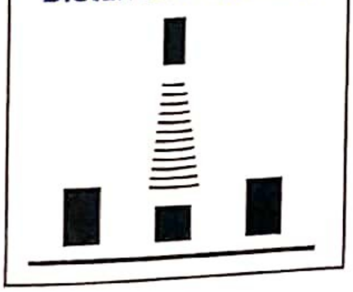
Switches

One or two switches can be selected. Either or both can be "PNP" or "NPN" type (sourcing or sinking). Each has independently adjustable set point, hysteresis, window, initial conditions, ON/OFF polarity, time delay and loss of target response.

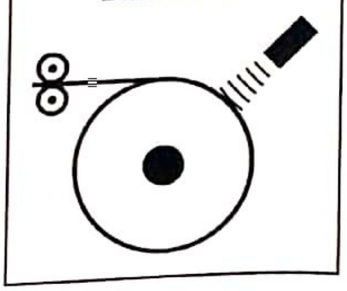
Level or Height



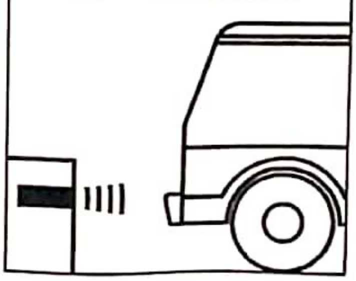
Distance-Proximity



Dimension



Object Detection



-677-3649 802-453-5522 FAX: 802-453-2549 52 Maple St., Bristol, VT 05443

web: www.senix.com e-mail: sales@senix.com

Senix® Distance Measurement

Senix® Corporation, 52 Maple St., Bristol, VT 05443 U.S.A.

Phone: 800-677-3649 or 802-453-5522 FAX: 802-453-2549

Web Site: http://www.senix.com e-mail: sales@senix.com

Senix® ToughSonic®/PC Distance Sensor

arget Performance

TSPC-30S1 Series

Maximum Range	4.3 meters (14 feet)
Optimum Range	102 mm - 3 meters (4 in. - 10 ft.)

TSPC-30S2 Series

Maximum Range	91 cm (36 in.)
Optimum Range	4.5 cm - 61 cm (1.75 in. - 24 in.)

Color/Transparency

Unaffected by color, transparency or optical characteristics.

Orientation

Detects flat or curved objects. Surface must reflect back to sensor. Flat surfaces are best when perpendicular to beam axis, and may not be detected at high angles of incidence.

Typical Distances - 30S1

Object	Max Range (m)
6.7 cm diam. cylinder	2.1
9 cm floppy disk	3.0
Liquid surface	4.3

onnections

Cable Connection	Wire	Description
Power	Brown	10-30 VDC @ 68 mA nominal (sensitivity reduced below 15 VDC)
Ground	Blue	Power and interface common
Voltage Output	White *	0-10 VDC, 0-5 VDC or custom range values between 0 and 10 VDC
Current Loop Output	Black *	4-20 mA or user adjusted range values between 0 and 20 mA
Switch #1 Output	Black *	Sinking ("NPN") or Sourcing ("PNP"), user selected
Switch #2 Output	White *	Sinking ("NPN") or Sourcing ("PNP"), user selected
RS-232 out / RS-485+	Gray	Serial data connection (depends on model - see model selection)
RS-232 in / RS-485-	Yellow	Serial data connection (depends on model - see model selection)

(*) Outputs on the black and white wires are SenixVIEW selected. The black wire options are 4-20 mA current loop or switch. White wire options are 0-10 VDC or switch. Switches can be sourcing or sinking.

ecifications

Optimum Range	102 mm - 3 meters (4 in. - 10 ft.)	**Max Range**	4.3 meters (14 feet)
Case Material	303 stainless steel	**Adjustment**	Button "teach" or SenixVIEW
Temperature	-40 to 70 C (-40 to 158 F)	**Configuration**	Stored in non-volatile memory
Humidity	0 to 100% operating	**Transducer**	Ruggedized piezoelectric
Compensation	Temperature compensated	**Protection**	NEMA-4X, NEMA-6P, IP68

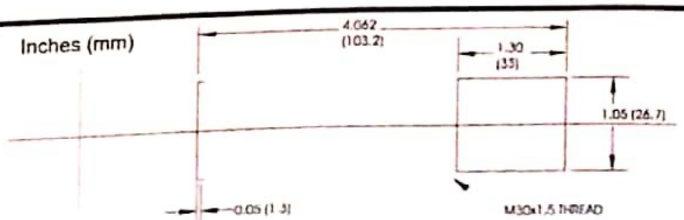
Resolution	Digital: 0.086 mm (0.003384 in.); Analog:4099 steps (over full 0-10 VDC or 0-20 mA)
Repeatability	Nominal 0.1% of range @ constant temp. Affected by target, distance, environment
Update Rate	50 ms, SenixVIEW adjustable; also affected by SenixVIEW filter selections
Voltage Output	0-10, 0-5 VDC or PC customized or push-button teachable endpoints, 10 mA max.
Current Loop	4-20 mA or PC customized, current sourcing, max. loop 500Ω, teachable endpoints
Sinking Switch	150 mA max. @ 40 VDC max., teachable set point & polarity, fault indication
Sourcing Switch	150 mA max. @ input voltage, teachable set point & polarity, fault indication
RS-232, RS-485	Modbus protocol, 9600-19200-38400 baud (selectable), 8 data bits, 1 stop, no parity
SYNC feature	Permits up to 32 sensors to operate in close proximity without interaction

rt Numbers

Model Number	Description
TSPC-30S1-232	Serial RS-232 interface (PC COM port compatible)
TSPC-30S1-485	Serial RS-485 interface (allows addressable multi-sensor networks)
TSPC-30S2-232	Serial RS-232 interface (PC COM port compatible)
TSPC-30S2-485	Serial RS-485 interface (allows addressable multi-sensor networks)

mensions

Inches (mm)



Dimensions are in inches (mm)

Mounting Hole: 30.5 mm (1.2 in.) diameter

Standard Cable: 2 m (6-ft)

Ships with instructions and two 30mm stainless mounting nuts (other options available)

This product is not recommended for applications with hazardous or explosive materials, or as a primary device for personal safety

Appendix C

Data Acquisition card 6024.

NOTE TO USERS

NATIONAL INSTRUMENTS

WHERE TO START WITH YOUR PCI-6023E/6024E/6025E

Thank you for buying a National Instruments PCI-6023E, PCI-6024E, or PCI-6025E board. The PCI-6025E features 16 channels (eight differential) of analog input, two channels of analog output, a 100-pin connector, and 32 lines of digital I/O. The PCI-6024E features 16 channels of analog input, two channels of analog output, a 68-pin connector and eight lines of digital I/O. The PCI-6023E is identical to the PCI-6024E, except that it does not have analog output channels. The PCI-6023E, PCI-6024E, and PCI-6025E kits include NI-DAQ driver software, which provides an extensive library of functions for digital I/O boards and other devices.

Documentation

PCI-6023E/6024E/6025E

For detailed information about the PCI-6023E, PCI-6024E, or PCI-6025E, see the *PCI-6023E/6024E/6025E User Manual.* This manual is available in electronic format on your NI-DAQ software distribution CD. If you prefer a hard copy of this manual, you can print it from the Acrobat reader or you can order a printed, bound copy from National Instruments (part number 322072A-01).

The user manual provides signal connection information, a hardware overview, and product specifications. The manual also contains warranty information and important warnings explaining the correct use of the PCI-6023E, PCI-6024E, and PCI-6025E.

NI-DAQ

If you are using NI-DAQ as your software interface to the PCI-6023E, PCI-6024E, or PCI-6025E, install the NI-DAQ software documentation from the NI-DAQ distribution CD in addition to installing the PCI-6023E/6024E/6025E hardware documentation.

322153A-01 *October 1998*

If you are using software other than NI-DAQ, use the documentation included with that software.

Installation

Software and Documentation

If you are using software other than NI-DAQ, consult your software documentation for software installation instructions.

Refer to the NI-DAQ release notes to install the NI-DAQ software and related documentation. When prompted during the software installation process to select components, select the option to install documentation. Choose the *PCI-6023E/6024E/6025E User Manual* and any other documents you want, such as the NI-DAQ software documents.

To install the hardware documentation without installing NI-DAQ software, deselect all components other than the documentation option.

Hardware

Note *Install your software before you install your board.*

After installing your software, you are ready to install your hardware. Your board will fit in any 5 V PCI expansion slot in your computer. However, to achieve best noise performance, leave as much room as possible between your board and other devices. The following are general installation instructions. Consult your computer user manual or technical reference manual for specific instructions and warnings.

1. Turn off and unplug your computer.
2. Remove the top cover of your computer.
3. Remove the expansion slot cover on the back panel of the computer.
4. Insert the board into a 5 V PCI slot. Gently rock the board to ease it into place. It may be a tight fit, but *do not force* the board into place.
5. Screw the mounting bracket of the board to the back panel rail of the computer.
6. Replace the top cover of your computer.
7. Plug in and turn on your computer.

The board is installed. You are now ready to configure your software. Refer to your software documentation for configuration instructions.

I/O Connector

Figure 1 shows the pin assignments for the 68-pin I/O connector on the PCI-6023E and PCI-6024E. It is also the MIO-16 68-pin connector available when you use the SH 1006868 cable assembly with the PCI-6025E.

ACH8	34	68	ACH0
ACH1	33	67	AIGND
AIGND	32	66	ACH9
ACH10	31	65	ACH2
ACH3	30	64	AIGND
AIGND	29	63	ACH11
ACH4	28	62	AISENSE
AIGND	27	61	ACH12
ACH13	26	60	ACH5
ACH6	25	59	AIGND
AIGND	24	58	ACH14
ACH15	23	57	ACH7
DAC0OUT[1]	22	56	AIGND
DAC1OUT[1]	21	55	AOGND
RESERVED	20	54	AOGND
DIO4	19	53	DGND
DGND	18	52	DIO0
DIO1	17	51	DIO5
DIO6	16	50	DGND
DGND	15	49	DIO2
+5 V	14	48	DIO7
DGND	13	47	DIO3
DGND	12	46	SCANCLK
PFI0/TRIG1	11	45	EXTSTROBE*
PFI1/TRIG2	10	44	DGND
DGND	9	43	PFI2/CONVERT*
+5 V	8	42	PFI3/GPCTR1_SOURCE
DGND	7	41	PFI4/GPCTR1_GATE
PFI5/UPDATE*	6	40	GPCTR1_OUT
PFI6/WFTRIG	5	39	DGND
DGND	4	38	PFI7/STARTSCAN
PFI9/GPCTR0_GATE	3	37	PFI8/GPCTR0_SOURCE
GPCTR0_OUT	2	36	DGND
FREQ_OUT	1	35	DGND

[1] Not available on the PCI-6023E

Figure 1. I/O Connector Pin Assignment for the PCI-6023E and PCI-6024E

Appendix D

Encoder E50S8.

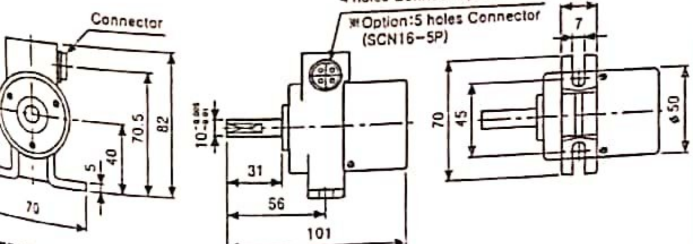
Specifications

Item			Shaft type the encoder to be mounted at the side(Incremental)	φ50mm Shaft type Incremental Rotary encoder	Wheel type the Incremental type Rotary encoder
Model	Totem pole output		ENA-□-3-T-□	E50S8-□-3-T-□	ENC-1-□-T-□
	NPN open collector output		ENA-□-3-N-□	E50S8-□-3-N-□	ENC-1-□-N-□
	Voltage output		ENA-□-3-V-□	E50S8-□-3-V-□	ENC-1-□-V-□
	Line driver output		—	E50S8-□-6-L-□	—
Resolution(P/R)			(Note1) •1, •2, •5, 10, •12, 15, 20, 23, 25, 30, 35, 40, 45, 50, 60, 75, 100, 120, 125, 150, 192, 200, 240, 250, 256, 300, 360, 400, 500, 512, 600, 800, 1000, 1024, 1200, 1500, 1800, 2000, 2048, 2500, 3000, 3600, 5000, 6000, 8000		1mm/Pulse, 1cm/Pulse, 1m/Pulse, 0.01yd/Pulse, 0.1yd/Pulse, 1yd/Pulse
Electrical specification	Output phase		A phase, B phase(Option : A, B, Z phase)	A, B, Z phase (Line driver output : A, $\overline{A}$, B, $\overline{B}$, Z, $\overline{Z}$ phase)	A phase, B phase
	Phase difference of output		Output between A and B phase : $\frac{T}{4} \pm \frac{T}{8}$ (T=1cycle of A phase)		
	Control output	Totem pole output	• Low ☞ Load current : Max. 30mA, Residual voltage : Max. 0.4VDC • High ☞ Load current : Max. 10mA, Output voltage(Power voltage 5VDC) : Min. (Power voltage−2.0)VDC, Output voltage(Power voltage 12−24VDC) : Min. (Power voltage−3.0)VDC		
		NPN open collector output	Load current : Max. 30mA, Residual voltage : Max. 0.4VDC		
		Voltage output	Load current : Max. 10mA, Residual voltage : Max. 0.4VDC		
		Line driver output	—	• Low ☞ Load current : Max. 20mA, Residual voltage : Max. 0.5VDC • High ☞ Load current : Max. −20mA, Output voltage : Min. 2.5VDC	—
	Response time (Rise/Fall)	Totem pole output	Max. 1μs(Cable length:2m, I sink=Max. 20mA)		
		NPN open collector output			
		Voltage output			
		Line driver output	—	Max. 0.5μs(Cable length:2m, I sink=Max. 20mA)	—
	Max. Response frequency		300kHz		180kHz
	Power supply		• 5VDC ±5%(Ripple P-P:Max. 5%) • 12−24VDC ±5%(Ripple P-P:Max. 5%)		
	Current consumption		Max. 60mA(disconnection of the load), Line driver output : Max. 50mA(disconnection of the load)		
	Insulation resistance		Min. 100MΩ(at 500VDC between all terminals and case)		
	Dielectric strength		750VAC 50/60Hz for 1 minute(Between all terminals and case)		
	Connection		Connector connection	Cable outgoing type, 250mm Cable outgoing connector type	
Mechanical specification	Starting torque		Max. 70gf · cm(0.007N · m)		Dependent on the coefficient of friction
	Moment of Inertia		Max. 80g · cm² (8×10⁻⁶kg · m²)		—
	Shaft loading		Radial : 10kgf, Thrust : 2.5kgf		
	Max. allowable revolution		(Note2) 5000rpm		
Vibration			1.5mm amplitude at frequency of 10 ~ 55Hz in each of X, Y, Z directions for 2 hours		
Shock			Max. 75G		
Ambient temperature			−10 ~ 70℃(at non-freezing status), Storage : −25 ~ 85℃		
Ambient humidity			35 ~ 85%RH, Storage : 35~90%RH		
Protection			IP50(IEC standard)		
Cable			φ5mm, 5P, Length:2m, Shield cable	φ5mm, 5P, Length:2m, Shield cable (Line driver output: φ5mm, 8P)	φ5mm, 5P, Length:2m, Shield cable
Accessory			φ10mm coupling	φ8mm coupling, Bracket	
Weight			Approx. 345g	Approx. 275g	Approx. 494g
Approval			CE (Except Line driver output)		

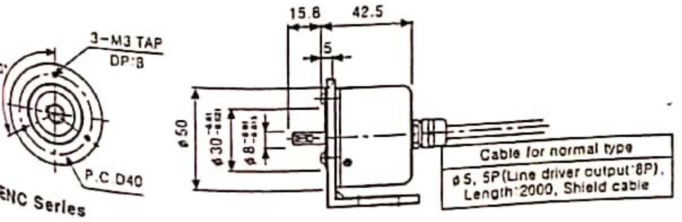
(Note1) 1, 2, 5, 12 P/R are output A and B phase only. (But Line driver output : A, $\overline{A}$, B, $\overline{B}$ phase)
(Note2) Max. allowable revolution ≥ Max. response revolution 【Max. response revolution(rpm) = $\frac{\text{Max. response frequency}}{\text{Resolution}} \times 60$ sec】
Please select the resolution to make lower max. revolution than max. allowable revolution.

Dimensions

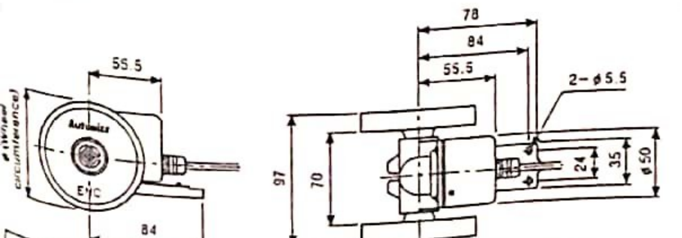
ENA Series



E50S8 Series



ENC Series



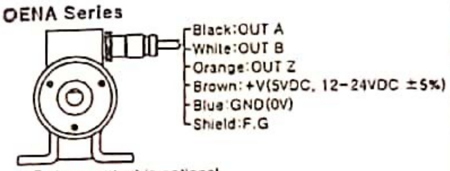
Cable for normal type
φ5, 5P, Length:2000, Shield cable

Wheel circumference	Min. measuring unit
250mm	1mm, 1cm, 1m
228.6mm(0.25yd)	0.01yd, 0.1yd, 1yd

(Unit:mm)

Connections

○ENA Series



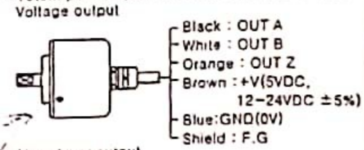
No	Connection	Color
①	A phase	Black
②	B phase	White
③	+V	Brown
④	0V	Blue
①	A phase	Black
②	B phase	White
③	Z phase	Orange
④	+V	Brown
⑤	0V	Blue

※Z phase output is optional.
※Non-using wires must be insulated.
※The shield cable and metal case of encoder must be grounded(F.G).

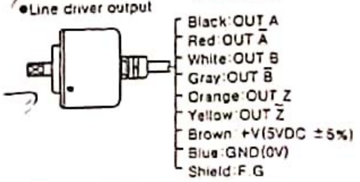
○E50S8 Series

■Normal type

●Totem pole output/ NPN open collector output/ Voltage output



●Line driver output

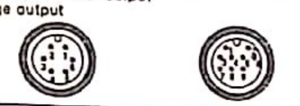


※Non-using wires must be insulated.
※The shield cable and metal case of encoder must be grounded(F.G).

■Cable outgoing connector type

●Totem pole output
NPN open collector output
Voltage output

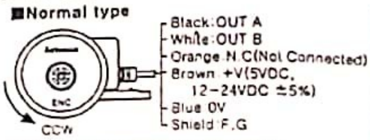
●Line driver output



Totem pole output / NPN open collector output / Voltage output			Line driver output		
Pin No	Cable color	Function	Pin No	Cable color	Function
①	Black	OUT A	①	Black	OUT A
②	White	OUT B	②	Red	OUT $\overline{A}$
③	Orange	OUT Z	③	Brown	+V
④	Brown	+V	④	Blue	GND
⑤	Blue	GND	⑤	White	OUT B
⑧	Shield	F.G	⑥	Gray	OUT $\overline{B}$
			⑦	Orange	OUT Z
			⑧	Yellow	OUT $\overline{Z}$
			⑨	Shield	F.G

○ENC Series

■Normal type



※Non-using wires must be insulated.
※The shield cable and metal case of encoder must be grounded(F.G).

■Cable outgoing connector type

Pin No	Cable color	Function
①	Black	OUT A
②	White	OUT B
③	Orange	N.C
④	Brown	+V
⑤	Blue	GND
⑥	Shield	F.G

Appendix E

Regulators used.

7805 Data Sheet

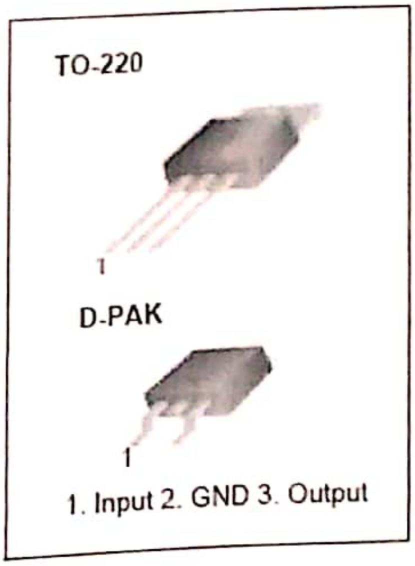
3-Terminal 1A Positive Voltage Regulator

Features

- Output Current up to 1A
- Output Voltages of 5, 6, 8, 9, 10, 12, 15, 18, 24V
- Thermal Overload Protection
- Short Circuit Protection
- Output Transistor Safe Operating Area Protection

Description

The KA78XX/KA78XXA series of three-terminal positive regulator are available in the TO-220/D-PAK package and with several fixed output voltages, making them useful in a
Wide range of applications. Each type employs internal current limiting, thermal shut down and safe operating area protection, making it essentially indestructible. If adequate
Heat sinking is provided; they can deliver over 1A output current. Although designed primarily as fixed voltage regulators, these devices can be used with external
Components to obtain adjustable voltages and currents.



Absolute Maximum Ratings

Parameter	Symbol	Value	Unit
Input Voltage (for V_O = 5V to 18V) (for V_O = 24V)	V_I V_I	35 40	V V
Thermal Resistance Junction-Cases (TO-220)	$R_{\theta JC}$	5	°C/W
Thermal Resistance Junction-Air (TO-220)	$R_{\theta JA}$	65	°C/W
Operating Temperature Range (KA78XX/A/R)	T_{OPR}	0 ~ +125	°C
Storage Temperature Range	T_{STG}	-65 ~ +150	°C

Electrical Characteristics (KA7805/KA7805R)

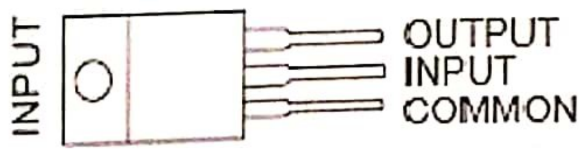
(Refer to test circuit ,0°C < T_J < 125°C, I_O = 500mA, V_I =10V, C_I= 0.33μF, C_O=0.1μF, unless otherwise specified)

Parameter	Symbol	Conditions		KA7805 Min.	KA7805 Typ.	KA7805 Max.	Unit
Output Voltage	V_O	T_J =+25 °C		4.8	5.0	5.2	V
		5.0mA ≤ Io ≤ 1.0A, Po ≤ 15W V_I = 7V to 20V		4.75	5.0	5.25	
Line Regulation (Note1)	Regline	T_J=+25 °C	V_O = 7V to 25V	-	4.0	100	mV
			V_I = 8V to 12V	-	1.6	50	
Load Regulation (Note1)	Regload	T_J=+25 °C	I_O = 5.0mA to1.5A	-	9	100	mV
			I_O =250mA to 750mA	-	4	50	
Quiescent Current	I_Q	T_J =+25 °C		-	5.0	8.0	mA
Quiescent Current Change	ΔI_Q	I_O = 5mA to 1.0A		-	0.03	0.5	mA
		V_I= 7V to 25V		-	0.3	1.3	
Output Voltage Drift	$\Delta V_O/\Delta T$	I_O= 5mA		-	-0.8	-	mV/ °C
Output Noise Voltage	V_N	f = 10Hz to 100KHz, T_A=+25 °C		-	42	-	μV/V_O
Ripple Rejection	RR	f = 120Hz V_O = 8V to 18V		62	73	-	dB
Dropout Voltage	V_{Drop}	I_O = 1A, T_J =+25 °C		-	2	-	V
Output Resistance	r_O	f = 1KHz		-	15	-	mΩ
Short Circuit Current	I_{SC}	V_I = 35V, T_A =+25 °C		-	230	-	mA
Peak Current	I_{PK}	T_J =+25 °C		-	2.2	-	A

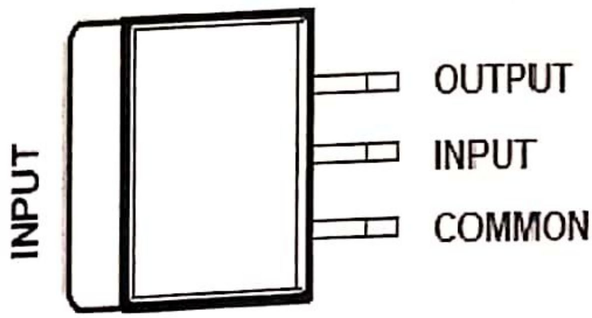
7905 Datasheet

Description/ordering information

This series of fixed-negative-voltage integrated-circuit voltage regulators is designed to complement Series μA7800 in a wide range of applications. These applications include on-card regulation for elimination of noise and distribution problems associated with single-point regulation. Each of these regulators can deliver up to 1.5 A of output
current. The internal current limiting and thermal shutdown features of these regulators essentially make them immune to overload. In addition to use as fixed-voltage regulators, these devices can be used with external components to obtain adjustable output voltages and currents and also as the power-pass element in precision



KTE PACKAGE
(TOP VIEW)



Electrical Characteristics

Vin=-10V, Io=500mA, CIn=2.2uF, Cout=1uF, 0°C≤Tj≤125°C (unless otherwise noted)

Symbol	Parameter	Conditions	H7905AE			Units
			Min	Typ	Max	
Vo	Output Voltage	Tj=25°C	-4.9	-5	-5.1	V
		PD≤15W, 5mA≤Io≤1A Vi=-8V to -20V	-4.85	-5	-5.15	
ΔVo	Line Regulation	Tj=25°C, -7V≤Vin≤-25V	-	-	50	mV
		Tj=25°C, -8V≤Vin≤12V	-	-	25	
ΔVo	Load Regulation	5mA≤Io≤1.5A	-	-	100	mV
		250mA≤Io≤750mA	-	-	50	
IQ	Quiescent Current	Io≤1A, Tj=25°C	-	3	8	mA
ΔIQ	Quiescent Current Change	5mA≤Io≤1A	-	-	0.5	mA
		-8V≤Vin≤-25V	-	-	1.3	
ΔVo / ΔT	Output Voltage Drift	Io=5mA	-	-0.4	-	mV/°C
Vn	Output Noise Voltage	Ta=25°C, 10Hz to 100KHz	-	100	-	uV
RR	Ripple Rejection	ΔVi=10V, f=120Hz	54	68	-	dB
VD	Dropout Voltage	Tj=25°C, Io=1A	-	2	-	V
Isc	Short Circuit Current	Tj=25°C, Vi=-35V	-	2.2	-	A
Ipk	Peak Output Current	Tj=25°C	1.3	2.2	-	A

Symbol	Parameter	Conditions	H7905BE			Units
			Min	Typ	Max	
Vo	Output Voltage	Tj=25°C	-4.8	-5	-5.2	V
		PD≤15W, 5mA≤Io≤1A Vi=-8V to -20V	-4.75	-5	-5.25	
ΔVo	Line Regulation	Tj=25°C, -7V≤Vin≤-25V	-	10	100	mV
		Tj=25°C, -8V≤Vin≤12V	-	5	50	
ΔVo	Load Regulation	5mA≤Io≤1.5A	-	-	100	mV
		250mA≤Io≤750mA	-	-	50	
IQ	Quiescent Current	Io≤1A, Tj=25°C	-	3	8	mA
ΔIQ	Quiescent Current Change	5mA≤Io≤1A	-	-	0.5	mA
		-8V≤Vin≤-25V	-	-	1.3	
ΔVo / ΔT	Output Voltage Drift	Io=5mA	-	-0.4	-	mV/°C
Vn	Output Noise Voltage	Ta=25°C, 10Hz to 100KHz	-	100	-	uV
RR	Ripple Rejection	ΔVi=10V, f=120Hz	54	68	-	dB
VD	Dropout Voltage	Tj=25°C, Io=1A	-	2	-	V
Isc	Short Circuit Current	Tj=25°C, Vi=-35V	-	2.2	-	A
Ipk	Peak Output Current	Tj=25°C	1.3	2.2	-	A

7824 Datasheet

TO-263-3 (S)

Top View

1. Input
2. GND
3. Output

Electrical Characteristics (LM7824)

(V_I=33V, I_O=500mA, 0°C ≤T_J≤125 °C, unless otherwise specified. (Note 1)

Parameter	Symbol	Conditions	MIN	TYP	MAX	UNIT
Output Voltage	V_O	T_J = 25 °C	23	24	25	V
Line Regulation	ΔV_O	V_I = 27V to 38V T_J = 25 °C		18	480	mV
		V_I = 30V to 36V T_J = 25 °C		6	240	
Load Regulation	ΔV_O	I_O = 5mA to 1.5A, 25 °C		12	480	mV
		I_O = 250mA to 750mA, 25 °C		4	240	
Ripple Rejection	RR	V_I = 28V to 38V, f=120Hz	50	66		dB
Output Noise Voltage	V_N	F= 10Hz to 100Hz TJ = 25 °C		170		µV
Dropout Voltage	V_D	T_J = 25 °C		2.0		V
Quiescent Current		T_J = 25 °C		4.6	8.0	mA
Quiescent Current Change	ΔI_Q	V_I = 27V to 38V, T_J = 25 °C			1.0	mA
		I_O = 5mA to 1.0A, T_J = 25 °C			0.5	