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LABORATORY GUIDE

Seesaw Experiment for MATLAB®/Simulink® Users

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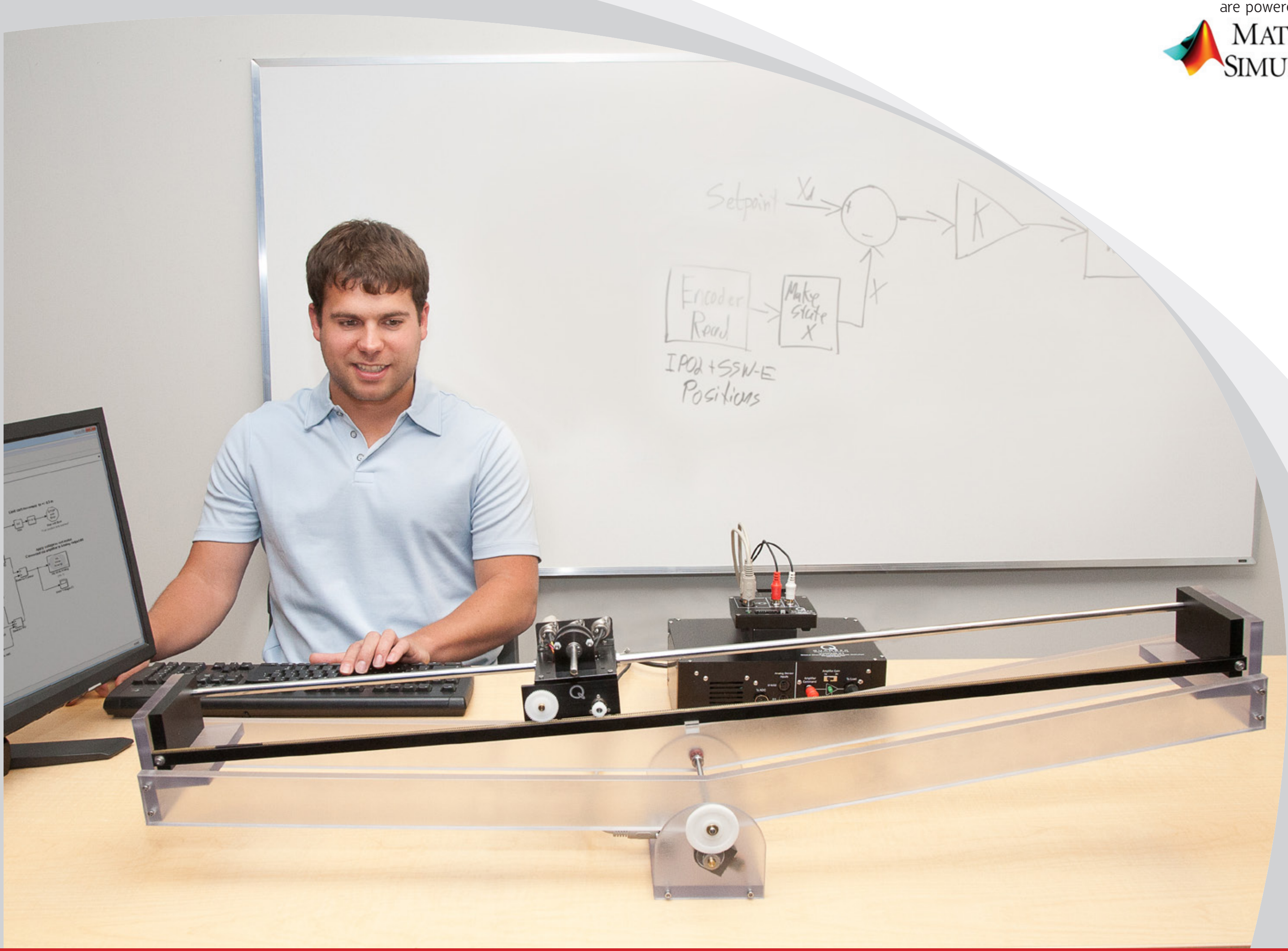

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1 INTRODUCTION

This laboratory manual describes how to design a state-feedback control system that can balance a seesaw using the IP02 linear servo cart.

The plant has two main components: the Quanser IP02 linear motion plant and the Quanser SEESAW-Emodule. The seesaw is composed of a long polycarbonate platform hinged onto a central pivot. An encoder is integrated into the pivot to measure the linear seesaw tilt angle.

Topics Covered

- Obtain a state-space representation of the open-loop system.
- Design and tune an LQR-based state-feedback controller satisfying the closed-loop system's desired design specifications.
- Simulate the system and ensure it is stabilized using the designed state-feedback control.
- Implement the state-feedback controller on the SEESAW system and evaluate its actual performance.

Prerequisites
In order to successfully carry out this laboratory, the user should be familiar with the following:

1. See the system requirements in Section 4 for the required hardware and software.
2. Modeling and state-space representation.
3. State-feedback design using Linear-Quadratic Regular (LQR) optimization.
4. Basics of Simulink®.
5. QUARC Integration lab detailed in Appendix A in the IP02 Lab Workbook [5].

2 BACKGROUND

2.1 Modeling

2.1.1 Model Convention

The linear seesaw model is shown in Figure 2.1. The SEESAW-E supports the IP02 Linear Servo Base Unit. The positive sense of rotation is defined to be counter-clockwise (CCW), when facing the linear cart and seesaw pinions. The positive direction of linear displacement of the IP02 cart is to the right when facing the cart. Finally, the zero angle tilt, θ = 0, of the seesaw corresponds to the seesaw perfectly horizontal.

The IP02 cart location is at linear position x_c, while the absolute position of the cart centre of mass is located at coordinates, (X_c, Y_c). The IP02 cart assembly has mass, m_c, and is actuated by an applied force, F_c. The total mass of the linear seesaw and the IP02 track is m_{sw}, with moment of inertia, J_{sw}. The centre of mass of the linear seesaw and IP02 track is located at absolute coordinates, (X_{sw}, Y_{sw}). The distance from the linear seesaw pivot and the centre of mass of the linear seesaw and IP02 track is, D_c. The IP02 track is located distance, D_t, above the linear seesaw pivot.

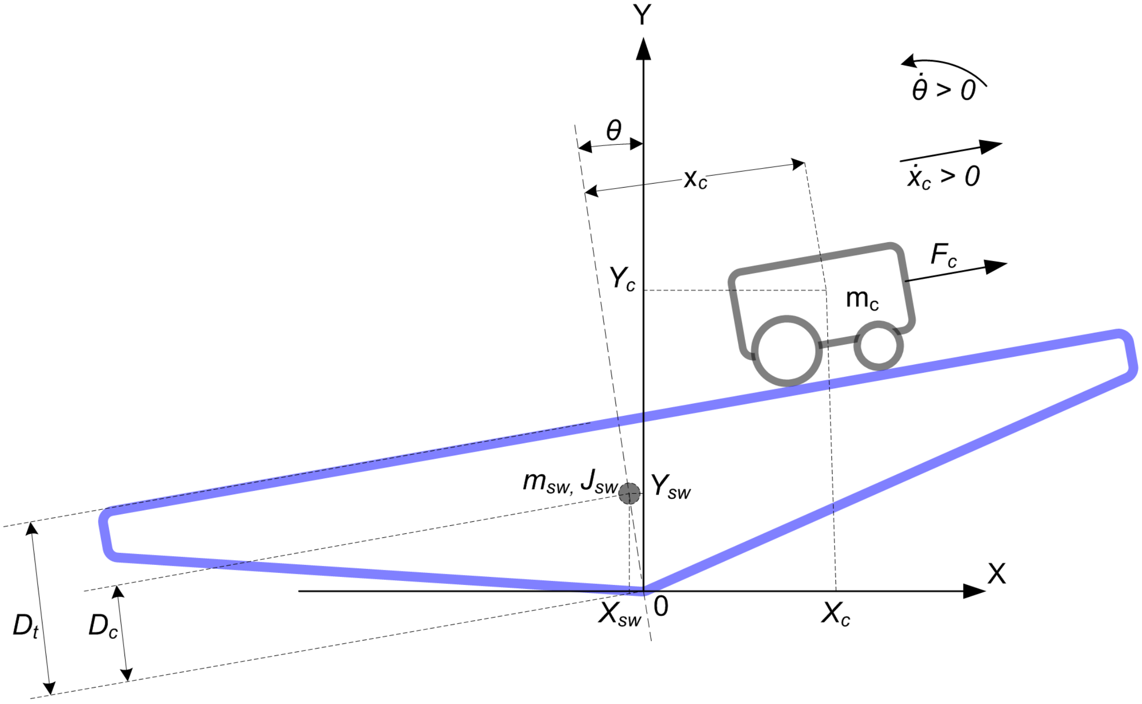


Figure 2.1: Linear Seesaw conventions

2.1.2 Nonlinear Equations of Motion

Instead of using classical mechanics, the Lagrange method is used to find the equations of motion of the system. This systematic method is often used for more complicated systems such as robot manipulators with multiple joints.

More specifically, the equations that describe the motions of the IP02 cart and the seesaw with respect to the servo motor voltage, i.e. the dynamics, will be obtained using the Euler-Lagrange equation:

$$\frac{\partial^2 L}{\partial t \partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i$$

The variables q_i are called *generalized coordinates*. For this system let

$$q(t)^\top = \begin{bmatrix} x_c(t) & \theta(t) \end{bmatrix}$$

where, as shown in Figure 2.1, $\theta(t)$ is the seesaw tilt angle and $x_c(t)$ is the linear cart position. The corresponding velocities are

$$\dot{q}(t)^\top = \begin{bmatrix} \frac{\partial x_c(t)}{\partial t} & \frac{\partial \theta(t)}{\partial t} \end{bmatrix}$$

Note: The dot convention for the time derivative will be used throughout this document, e.g., $\dot{\theta} = \frac{d\theta}{dt}$. The time variable t will also be dropped from θ and x_c, i.e., $\theta = \theta(t)$, $x_c = x_c(t)$.

With the generalized coordinates defined, the Euler-Lagrange equations for the rotary pendulum system are

$$\begin{aligned} \frac{\partial^2 L}{\partial t \partial \dot{x_c}} - \frac{\partial L}{\partial x_c} &= Q_1 \\ \frac{\partial^2 L}{\partial t \partial \dot{\theta}} - \frac{\partial L}{\partial \theta} &= Q_2 \end{aligned}$$

The Lagrangian of the system is described

$$L = T - V$$

where T is the total kinetic energy of the system and V is the total potential energy of the system. Thus the Lagrangian is the difference between a system's kinetic and potential energies.

The generalized forces Q_i are used to describe the non-conservative forces (e.g., friction) applied to a system with respect to the generalized coordinates. In this case, the generalized force acting on the linear cart is

$$Q_1 = F_c - B_{eq}\dot{x}_c, \tag{2.1}$$

and the force acting on the seesaw is

$$Q_2 = -B_{sw}\dot{\theta}. \tag{2.2}$$

Our control variable is the input servo motor voltage, V_m. Opposing the applied force resultant from the motor voltage is the equivalent damping, corresponding to the term B_{eq}. Since the seesaw is not actuated, the only force acting on the link is the damping, B_{sw}.

The Euler-Lagrange equations is a systematic method of finding the equations of motion, i.e., EOMs, of a system. Once the kinetic and potential energy are obtained and the Lagrangian is found, then the task is to compute various derivatives to get the EOMs. After going through this process, the nonlinear equations of motion for the system can be obtained. **See the supplied Maple worksheet (or its equivalent HTML representation) for the complete derivation.**

Based on the system schematic shown in Figure 2.1 and the generalized forces Equation 2.1 and Equation 2.2, the first Lagrange equation can be expressed as:

$$m_c\ddot{x}_c - m_c D_t\ddot{\theta} - m_c x_c\dot{\theta}^2 + g m_c \sin(\theta) = F_c - B_{eq}\dot{x}_c,$$

and the second Lagrage equation can be more explicitly expressed as shown below:

$$m_c\ddot{\theta}x_c^2 + 2m_c\dot{x}_c\dot{\theta} + g m_c \cos(\theta)x_c - m_c D_t\ddot{x}_c + (J_{sw} + m_c D_t^2)\ddot{\theta} + g(-m_c D_t \sin(\theta) - m_{sw} D_c \sin(\theta)) = -B_{sw}\dot{\theta}$$

Solving the two Lagrange equations for the second-order time derivative of the Lagrangian coordinates results in the following non-linear equations:

$$\begin{aligned}\ddot{x}_c &= \frac{1}{(m_c x_c^2 + J_{sw})m_c}\Big(m_c^2 x_c^3 \dot{\theta}^2 + (F_c m_c - g m_c^2 \sin(\theta) - B_{eq}\dot{x}_c m_c)x_c^2 + (-2m_c^2 D_t \dot{x}_c \dot{\theta} + \\ &\quad (m_c^2 D_t^2 + m_c J_{sw})\dot{\theta}^2 - m_c^2 D_t g \cos(\theta))x_c + (-m_c D_t^2 B_{eq} - BeqJ_{sw})\dot{x}_c - m_c D_t g m_{sw} D_c \sin(\theta)\Big)\end{aligned}$$

and

$$\ddot{\theta} = \frac{1}{m_c x_c^2 + J_{sw}}\left((D_t m_c \dot{\theta}^2 - 2m_c \dot{x}_c \dot{\theta} - g m_c \cos(\theta))x_c + D_t F_c - D_t B_{eq}\dot{x}_c + g m_{sw} D_c \sin(\theta) - B_{sw}\dot{\theta}\right)$$

The force applied to the linear cart, F_c, is generated by the servo motor as described by the equation

$$F_c = \left(\frac{\eta_g K_g K_t}{R_m r_{mp}}\right)\left(-\frac{K_g K_m \dot{x}_c}{r_{mp}} + \eta_m V_m\right) \tag{2.3}$$

See [2] for a description of the corresponding IP02 parameters (e.g. such as the back-emf constant, K_m).

2.1.3 Linearizing

Here is an example of how to linearize a two-variable nonlinear function called $f(z)$. Variable z is defined

$$z^\top = [z_1 \; z_2]$$

and $f(z)$ is to be linearized about the operating point

$${z_0}^\top = [a \; b]$$

The linearized function is

$$f_{lin} = f(z_0) + \left(\frac{\partial f(z)}{\partial z_1}\right)\Bigg|_{z=z_0}(z_1 - a) + \left(\frac{\partial f(z)}{\partial z_2}\right)\Bigg|_{z=z_0}(z_2 - b)$$

2.1.4 Linear State-Space Model

The linear state-space equations are

$$\dot{x} = Ax + Bu \tag{2.4}$$

and

$$y = Cx + Du \tag{2.5}$$

where x is the state, u is the control input, A, B, C, and D are state-space matrices. For the linear seesaw system, the state and output are defined

$$x^\top = \begin{bmatrix} x_c & \theta & \dot{x}_c & \dot{\theta} \end{bmatrix}$$

and

$$y^\top = \begin{bmatrix} x_1 & x_2 \end{bmatrix}.$$

After linearizing the nonlinear equations of motion about the zero tilt (balanced) position, and substituting the state given in Equation 2.1.4, we obtain the following state-space matrices:

$$A = \frac{1}{J_{sw}}\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -m_c D_t g & \dfrac{-g m_c J_{sw} + m_c D_t g m_{sw} D_c}{m_c} & \dfrac{-m_c D_t^2 B_{eq} - B_{eq} J_{sw}}{m_c} & -D_t B_{sw} \\ -g m_c & g m_{sw} D_c & -D_t B_{eq} & -B_{sw} \end{bmatrix}$$

and

$$B = \frac{1}{J_{sw}} \begin{bmatrix} 0 \\ 0 \\ \frac{J_{sw} + m_c D_t^2}{m_c} \\ D_t \end{bmatrix}.$$

In the output equation, only the position of the linear servo cart and seesaw tilt angle are being measured. Based on this, the C and D matrices in the output equation are

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{2.6}$$

and

$$D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{2.7}$$

Note: The velocities of the servo and seesaw angle can be computed in the digital controller, e.g., by taking the derivative and filtering the result though a high-pass filter.

2.2 Control

In Section 2.1, we found a linear state-state space model that represents the SEESAW-E system. This model is used to investigate the stability properties of the system in Section 2.2.1. In Section 2.2.2, the notion of controllability is introduced. Using the Linear Quadratic Regular algorithm, or LQR, is a common way to find the control gain and is discussed in Section 2.2.3. Lastly, Section 2.2.4 describes the state-feedback control used to control the servo position while minimizing link deflection.

2.2.1 Stability

The stability of a system can be determined from its poles ([7]):

- Stable systems have poles only in the left-hand plane.
- Unstable systems have at least one pole in the right-hand plane and/or poles of multiplicity greater than 1 on the imaginary axis.
- Marginally stable systems have one pole on the imaginary axis and the other poles in the left-hand plane.

The poles are the roots of the system's characteristic equation. From the state-space, the characteristic equation of the system can be found using

$$\text{det}\,(sI - A) = 0 \tag{2.8}$$

where *det()* is the determinant function, s is the Laplace operator, and I the identity matrix. These are the *eigenvalues* of the state-space matrix A.

2.2.2 Controllability

If the control input, u, of a system can take each state variable, x_i where $i = 1 \dots n$, from an initial state to a final state then the system is controllable, otherwise it is uncontrollable ([7]).

Rank Test The system is controllable if the rank of its controllability matrix

$$T = \left[B\ AB\ A^2B \dots A^nB\right] \tag{2.9}$$

equals the number of states in the system,

$$\text{rank}(T) = n. \tag{2.10}$$

2.2.3 Linear Quadratic Regular (LQR)

If (A,B) are controllable, then the Linear Quadratic Regular optimization method can be used to find a feedback control gain. Given the plant model in Equation 2.4, find a control input u that minimizes the cost function

$$J = \int_0^\infty x(t)'Qx(t) + u(t)'Ru(t)\,dt, \tag{2.11}$$

where Q and R are the weighting matrices. The weighting matrices affect how LQR minimizes the function and are, essentially, tuning variables.

Given the control law $u = -Kx$, the state-space in Equation 2.4 becomes

$$\begin{aligned} \dot{x} &= Ax + B(-Kx) \\ &= (A - BK)x \end{aligned}$$

2.2.4 Feedback Control

The feedback control loop that in Figure 2.2 is designed to balance the seesaw by regulating the seesaw tilt angle, θ.

The reference state is defined

$$x_d = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}$$

and the controller is therefore

$$u = -Kx, \tag{2.12}$$

which is the control used in the LQR algorithm.

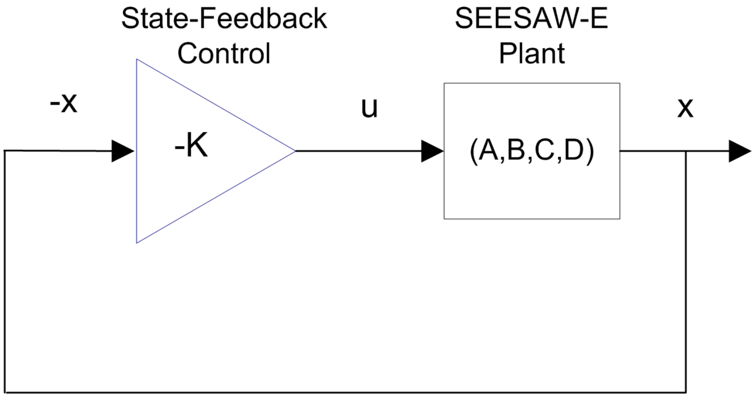


Figure 2.2: State-feedback control loop

To eliminate servo tracking error, we can augment the system to include an integrator such that

$$\dot{\eta} = \begin{bmatrix} A & 0 \\ 1 & 0 \end{bmatrix} \eta + \begin{bmatrix} B \\ 0 \end{bmatrix} u$$

where A and B are the state-space matrices defined in Section 2.1.4 and the states are

$$\eta^\top = \begin{bmatrix} x_c & \theta & \dot{x}_c & \dot{\theta} & \int \theta \, \mathrm{d}t \end{bmatrix}$$

This introduces the integration terms $\eta_7(t) = \int \theta \, \mathrm{d}t$ to the feedback controller

$$u = K(-\eta).$$

3 LAB EXPERIMENTS

3.1 Simulation

In this section we will use the Simulink diagram shown in Figure 3.1 to simulate the closed-loop control of the SEESAW-E system. The system is simulated using the linear model summarized in Section 2.1. The Simulink model uses the state-feedback control described in Section 2.2.4. The feedback gain K is found using the Matlab LQR command (LQR is described briefly in Section 2.2.3). The goal is to make sure the gain used successfully stabilizes the system (i.e., keeps it balanced), and does not saturate the dc motor.

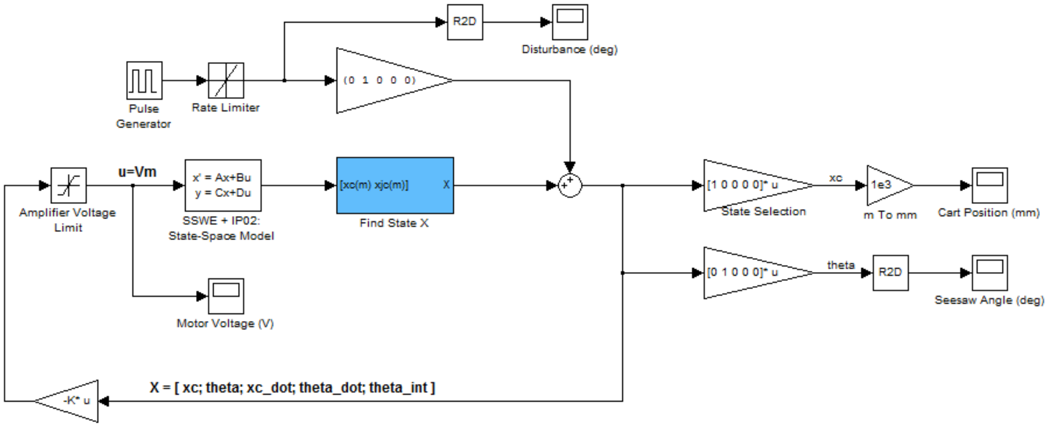


Figure 3.1: Simulink model used to simulate SEESAW-E.

The state-feedback controller has proportional-derivative (PD) action and the integral (I) action. The *Find State X* block shown in Figure 3.1 creates the complete state vector using a differentiating filter and integral block. The position and velocity states of the model are then multiplied by the vector gain k computed in earlier in, i.e., $k(1:5) = [k1, k2, k3, k4, k5]$. The *Pulse Generator* introduces a 4.5 degree disturbance into the system every four seconds to simulate tapping the seesaw.

IMPORTANT: Before you can conduct these experiments, you need to make sure that the lab files are configured according to your setup. If they have not been configured already, then you need to go to Section 4 to configure the lab files first.

3.1.1 Procedure

Follow these steps to simulate the system:

1. Make sure the LQR weighting matrices in setup_sswe.m are set to

$$Q = \begin{bmatrix} 1000 & 0 & 0 & 0 & 0 \\ 0 & 5000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2000 \end{bmatrix}$$

   and

$$R = 0.5.$$

2. Run the script to generate the gain

$$K = \begin{bmatrix} 180.797 & -224.3485 & 16.6684 & -66.9969 & -63.2456 \end{bmatrix}.$$

LQR Tuning: When tuning the LQR, we start with the identity matrix. To put more emphasis on the seesaw tilt angle θ, we set $Q(2,2) = 5000$. The last diagonal element, $Q(5,5)$ is set to 2000 to generate an integral gain for the seesaw tilt regulation.

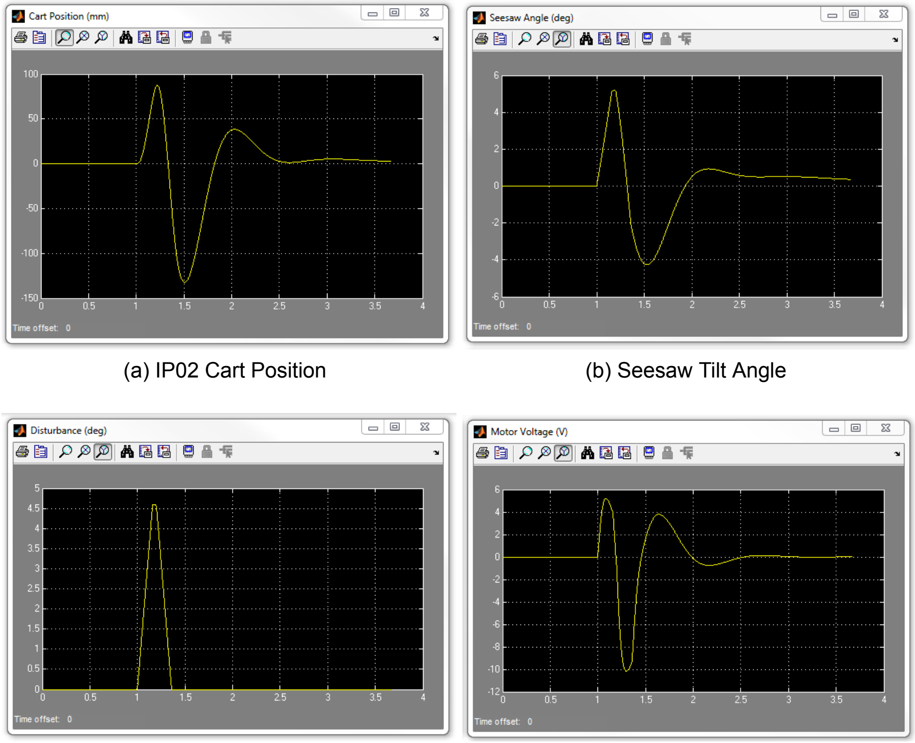
3. To generate a 4.5 degree disturbance, ensure the *Pulse Generator* is set to the following:

   - Amplitude = 0.08 rad
   - Period = 4
   - Pulse Width = 5 %
   - Phase Delay = 1

   and that the *Rate Limiter* has a rising and falling slew rate of 0.5 rad/s.

4. Open the cart position scope, *Cart Position (mm)*, the seesaw angle scope, *Seesaw Angle (deg)*, the disturbance scope, *Disturbance (deg)*, and the motor input voltage scope, *Vm (V)*.

5. Start the simulation. The scopes should be displaying responses similar to Figure 3.2.



(a) IP02 Cart Position

(b) Seesaw Tilt Angle

(c) Disturbance

(d) Voltage

Figure 3.2: Simulated closed-loop response.

3.1.2 Analysis

The feedback response is shown in Figure 3.3. You can generate this figure by running the plot command.

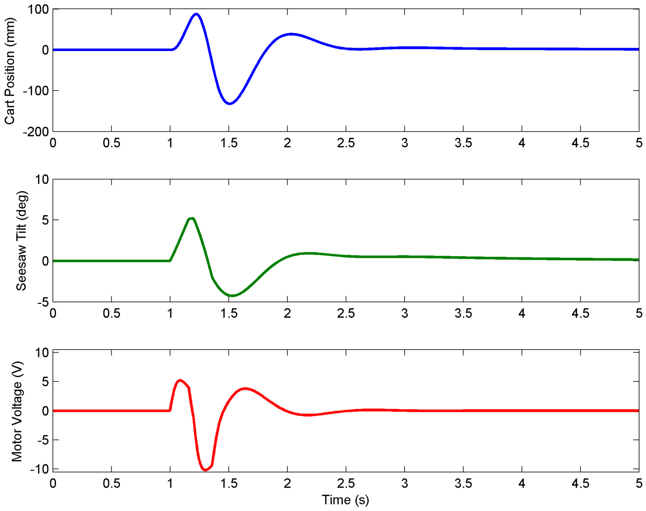


Figure 3.3: Simulated SEESAW-E feedback response.

As shown by the response in Figure 3.3, the seesaw maintains its balanced horizontal position.

Generating the Matlab figure: After each simulation run, each scope automatically saves their response to a variable in the Matlab®workspace. The *Cart Position (mm)* scope saves its response to the variable called *data_xc*, the *Seesaw Angle (deg)* scope saves its data to the *data_theta* variable, the *Disturbance (deg)* scope saves its data to the *data_dist* variable, and the *Vm (V)* scope saves its plot to the *data_vm* variable.

3.2 Implementation

The q_sswe Simulink diagram shown in Figure 3.4 is used to perform the balance control on the SEESAW. The *SEESAW-E + IP02* subsystem contains QUARC®blocks that interface with the DC motor and sensors of the SEESAW system.

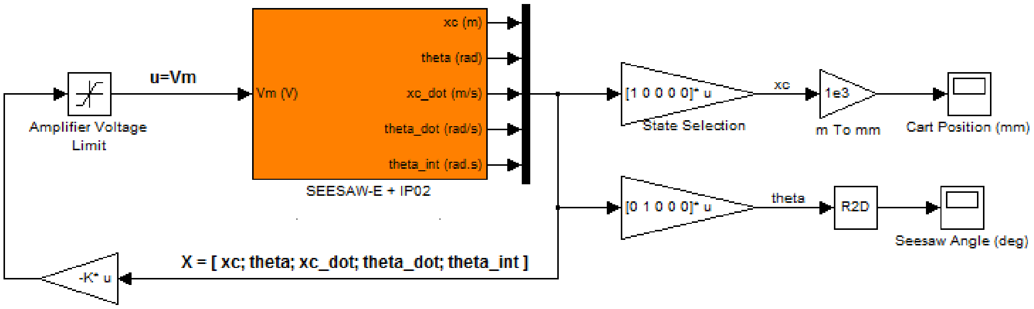


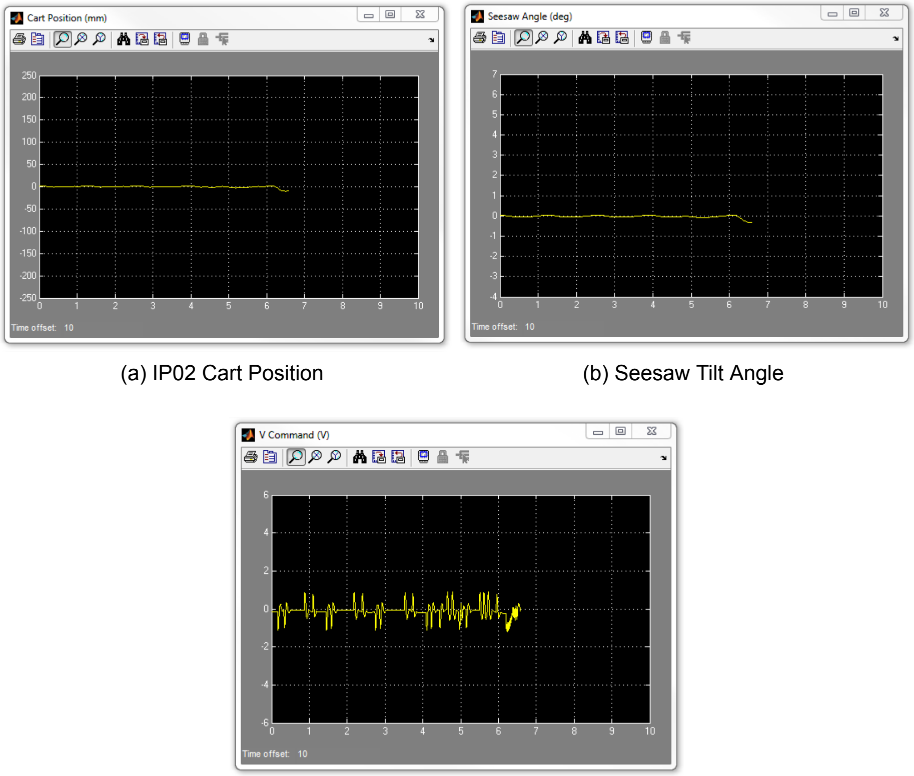
Figure 3.4: Simulink model used with QUARC®to run controller on the SEESAW.

IMPORTANT: Before you can conduct these experiments, you need to make sure that the lab files are configured according to your setup. If they have not been configured already, then you need to go to Section 4 to configure the lab files first.

3.2.1 Procedure

Follow this procedure:

1. Run the setup_ip02_ssw.m script using the LQR weighting matrices that you used in the simulation in Section 3.1.
2. Open the linear cart position scope, *Cart Position (mm)*, the seesaw angle scope, *Seesaw Angle (deg)*, and the motor input voltage scope, *V Command (V)*.
3. In the Simulink diagram, go to QUARC | Build.
4. **Make sure that the seesaw is horizontal, and the cart is close to the centre of the track.**
5. Click on QUARC | Start to run the controller.
6. Release the seesaw. The scopes should be displaying responses similar to Figure 3.5.



(a) IP02 Cart Position

(b) Seesaw Tilt Angle

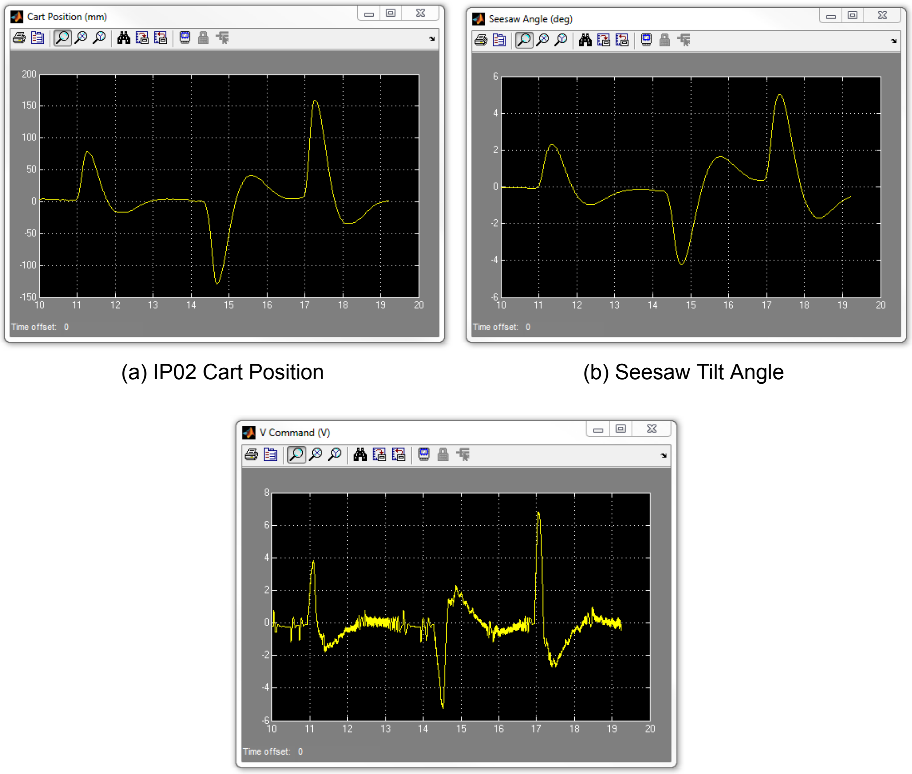
(c) Voltage

Figure 3.5: Typical response when balancing the SEESAW system

7. In order to verify that the LQR tuned response satisfies your design specifications, an external disturbance needs to be introduced. Once the system has stabilized, gently tap the seesaw to introduce a disturbance of about ±5 degrees from the horizontal equilibrium position. The system response should resemble the scopes shown in Figure 3.6.
8. If your specifications have not been met, you can finely tune the LQR weighting matrices on-the-fly using the following command:

   ```
   >> K = lqr(A,B, diag([Q(1,1),Q(1,1),Q(3,3),Q(4,4),Q(5,5)]),R)
   ```

9. To stop the experiment, click on the QUARC | Stop button but **make sure you catch the seesaw before it swings down**. This will prevent the assembly from hitting the table surface.



(a) IP02 Cart Position

(b) Seesaw Tilt Angle

(c) Voltage

Figure 3.6: Typical response when disturbing the SEESAW system

3.2.2 Analysis

An example of the closed-loop balance response, as opposed to the disturbance response, is shown in Figure 3.7. You can generate this using the plot command after running the q_sswe QUARC controller.

Due to the friction in the system, the servo oscillates back-and-forth approximately ±0.05 degrees to balance the seesaw. Because of the integrator, the seesaw eventually stabilizes about the 0 degree setpoint.

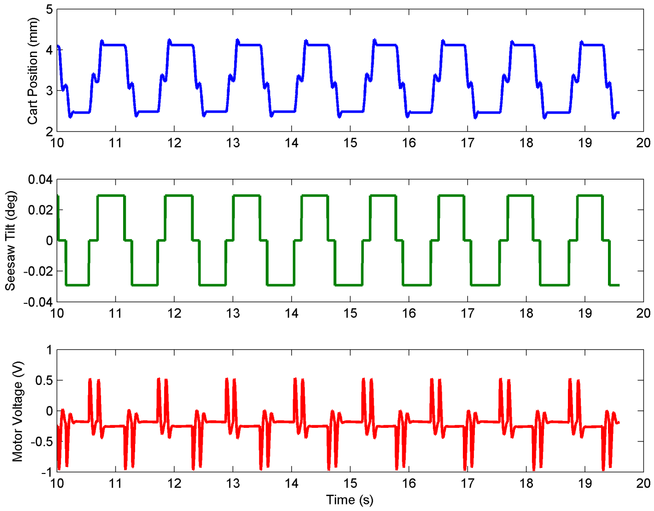


Figure 3.7: SEESAW balance control response

4 SYSTEM REQUIREMENTS

Required Software

- Microsoft Visual Studio (MS VS)
- Matlab® with Simulink®, Real-Time Workshop, and the Control System Toolbox
- QUARC®

See the QUARC®software compatibility chart in [4] to see what versions of MS VS and Matlab are compatible with your version of QUARC and for what OS.

Required Hardware

- Data acquisition (DAQ) device **with 2x encoder inputs** and that is compatible with QUARC®. This includes Quanser DAQ boards such as Q8-USB, QPID, and QPIDe and some National Instruments DAQ devices. For a full listing of compliant DAQ cards, see Reference [1].
- Quanser IP02 linear servo.
- Quanser SEESAW-E (positioned underneath the IP02).
- Quanser VoltPAQ-X1 power amplifier, or equivalent.

Before Starting Lab

Before you begin this laboratory make sure:

- QUARC®is installed on your PC, as described in [3].
- DAQ device has been successfully tested (e.g., using the test software in the Quick Start Guide or the *QUARC Analog Loopback Demo*).
- SEESAW-E and amplifier are connected to your DAQ board as described its User Manual [6].

4.1 Overview of Files

File Name	Description
SEESAW-E User Manual.pdf	This manual describes the hardware of the SEESAW system and explains how to setup and wire the system for the experiments.
SEESAW-E Laboratory Guide.pdf	This document demonstrates how to obtain the linear state-space model of the system, simulate the closed-loop system, and implement controllers on the SEESAW plant using QUARC®.
setup_ip02_ssw.m	The main Matlab script that sets the IP02 motor and sensor parameters, the IP02 configuration-dependent model parameters, and the SEESAW sensor parameters. Run this file only to setup the laboratory.
config_ip02.m	Returns the configuration-based IP02 model specifications Rm, Kt, Km, Kg, eta_g, Beq, Jeq, Jm, r_mp, and eta_m, the sensor calibration constant K_EC, and the amplifier limits VMAX_AMP and IMAX_AMP.
config_ssw.m	Returns the seesaw model parameters.
s_sswe.mdl	Simulink file that simulates the closed-loop control of a SEESAW-E system using state-feedback control.
q_sswe.mdl	Simulink file that implements the state-feedback control on the SEESAW-E system using QUARC®.
SEESAW.mws	Maple worksheet used to develop the model for the SEESAW experiment. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
SEESAW.html	HTML presentation of the Maple Worksheet. It allows users to view the content of the Maple file without having Maple 9 installed. No modifications to the equations can be performed when in this format.

Table 4.1: Files supplied with the SEESAW

4.2 Setup for Simulation

Before beginning the in-lab procedure outlined in Section 3.1, the s_sswe Simulink diagram and the setup_ip02_ssw.m script must be configured.

Follow these steps:

1. Load the Matlab software.
2. Browse through the *Current Directory* window in Matlab and find the folder that contains the file *setup_ip02_ssw.m*.
3. Open the *setup_ip02_ssw.m* script.
4. **Configure setup_ip02_ssw script**: When used with the SEESAW, the IP02 has no load (additional weight). Make sure the script is setup to match this setup:
   - IP02_WEIGHT_TYPE to 'NO_WEIGHT'
   - K_AMP to 1 (unless your amplifier gain is different)
   - AMP_TYPE to your amplifier type (e.g., VoltPAQ).
   - Ensure other parameters such as VMAX_DAC match your system configuration.

5. Run setup_ip02_ssw.m to setup the Matlab workspace.
6. Open the *s_sswe.mdl* Simulink diagram, shown in Figure 3.1.

4.3 Setup for Running on SEESAW

Before performing the in-lab exercises in Section 3.2, the q_sswe Simulink diagram and the setup_ip02_ssw.m script must be configured.

Follow these steps to get the system ready for this lab:

1. Setup the IP02 with the SEESAW module as detailed in the SEESAW User Manual [6].
2. **Make sure the seesaw is horizontal, and the IP02 cart is close to the centre of the track**. For more information, go to the SEESAW User Manual [6].
3. Configure and run setup_ip02_ssw.m as explained in Section 4.2.
4. Open the *q_sswe.mdl* Simulink diagram, shown in Figure 3.4.
5. **Configure DAQ:** Ensure the HIL Initialize block in the *SEESAW-E + IP02* subsystem is configured for the DAQ device that is installed in your system. See Reference [1] for more information on configuring the HIL Initialize block.

REFERENCES

[1] Quanser Inc. *QUARC User Manual*.

[2] Quanser Inc. *IP02 User Manual*, 2009.

[3] Quanser Inc. *QUARC Installation Guide*, 2009.

[4] Quanser Inc. *QUARC Compatibility Table*, 2010.

[5] Quanser Inc. *IP02 Lab Workbook (QUARC)*, 2012.

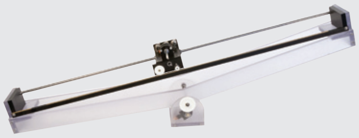
[6] Quanser Inc. *SEESAW-E User Manual*, 2012.

[7] Norman S. Nise. *Control Systems Engineering*. John Wiley & Sons, Inc., 2008.

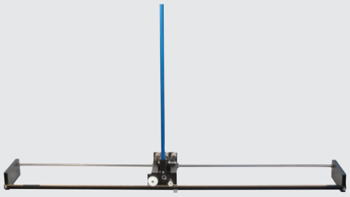
Nine linear motion plants for teaching fundamental and advanced controls concepts

IP02 Base Unit

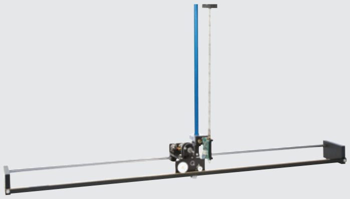
Seesaw



Linear Pendulum



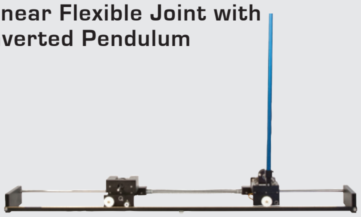
Linear Flexible Inverted Pendulum



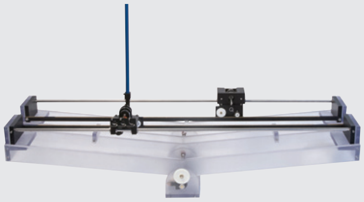
Linear Double Inverted Pendulum

Linear Flexible Joint

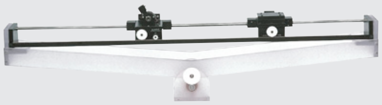
Linear Flexible Joint with Inverted Pendulum



Seesaw Pendulum



Linear Flexible Joint on Seesaw



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