LABORATORY GUIDE

Linear Flexible Inverted Pendulum Experiment for LabVIEW™ Users

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CONTENTS

1 INTRODUCTION

This laboratory manual describes how to design a state-feedback control system that can balance a stiff and flexible pendulum simultaniously using the IP02 linear servo cart.

The plant has two main components: the Quanser IP02 linear motion plant and the Quanser Flexible Pendulum-module. The flexible pendulum is a flexible link with an end weight and a strain gauge to measure the deflection of the link. The stiff pendulum is the long pendulum described in the SPG and SIP User Manual [2].

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 FLEXPEN 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 LabVIEW^{TM} .

5. LabVIEW Integration lab detailed in Appendix A in the IP02 Laboratory Workbook [4].

2 BACKGROUND

2.1 Modeling

2.1.1 Model Convention

The flexible pendulum model is shown in Figure 2.1. The FLEXPEN is attached to the IP02 Linear Servo Base Unit pendulum pivot. The positive sense of rotation is defined to be counter-clockwise (CCW), when facing the linear cart pinions. The positive direction of linear displacement of the IP02 cart is to the right when facing the cart. Finally, the zero angle of the stiff pendulum and deflection, $\theta = 0$ and $\gamma = 0$, corresponds to the two pendulums perfectly balanced vertically.

The IP02 cart location is at linear position x_c. The IP02 cart assembly has mass, m_c, and is actuated by an applied force, F_c. The pendulums have masses m_{sp} and m_{fp} located at their respective centres of mass, (x_{sp}, y_{sp}) and (x_{fp}, y_{fp}). The angle of deflection of the flexible pendulum, γ, is defined as the angle between the stiff pendulum and a line between the pivot and tip of the flexible pendulum. The deflection of the flexible link, x_{def}, is defined as the distance between the tip of the stiff pendulum, and the tip of the flexible pendulum.
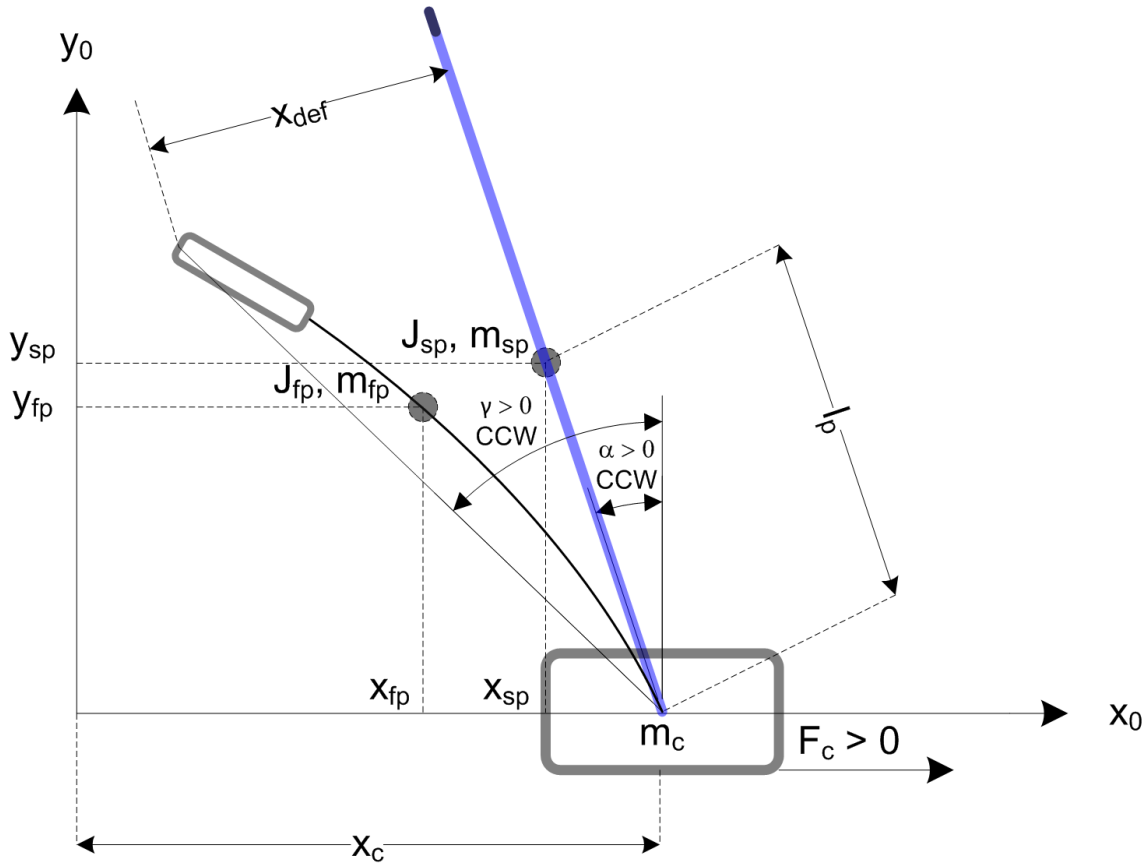

Figure 2.1: Flexible pendulum conventions

The Cartesian coordinates of the stiff pendulum centre of mass are

$$x_{sp} = x_c - l_{sp}\sin(\alpha)$$

$$y_{sp} = l_{sp}\cos(\alpha)$$

where l_{sp} is the distance of the centre of mass from the pivot point. Similarly, the coordinates of the flexible pendulum

centre of gravity are

$$x_{fp} = x_c - l_{sp}\sin(\alpha) - l_{fp}\sin(\gamma)$$
$$y_{fp} = l_{sp}\cos(\alpha) + l_{fp}\cos(\gamma)$$

where l_{fp} is the distance of the flexible link centre of mass from the pivot point.

The strain gauge sensor measures the linear deflection of the tip. The angle of deflection is small, and therefore the small angle approximation $\sin(x) \approx x$ can be used. Thus

$$\gamma = \frac{x_{def}}{L_{link}}$$

where L_{link} is the distance from the position on the flexible link where the strain gage begins to measure, to the tip of the link. This translates into the length of the flexible link that can me measured.

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, flexible pendulum, and stiff pendulum 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

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

where, as shown in Figure 2.1 $\alpha(t)$ is the stiff pendulum angle, γ is the flexible link deflection angle, and $x_c(t)$ is the linear cart position. The corresponding velocities are

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

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

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

$$\frac{\partial^2 L}{\partial t \partial \dot{x}_c} - \frac{\partial L}{\partial x_c} = Q_1$$
$$\frac{\partial^2 L}{\partial t \partial \dot{\alpha}} - \frac{\partial L}{\partial \alpha} = Q_2$$
$$\frac{\partial^2 L}{\partial t \partial \dot{\gamma}} - \frac{\partial L}{\partial \gamma} = Q_2$$

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 viscous damping forces are neglected, and the generalized forces acting on the system are thus:

$$Q_1 = F_c, \tag{2.1}$$

$$Q_2 = 0, \tag{2.2}$$

and

$$Q_3 = 0. \tag{2.3}$$

Our control variable is the input servo motor voltage, V_m.

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, Equation 2.2 and Equation 2.2, the first Lagrange equation can be expressed as:

$$(m_{sp}l_{sp}\sin(\alpha) + m_{fp}l_{sp}\sin(\alpha))\dot{\alpha}^2 + m_{fp}l_{fp}\sin(\gamma)\dot{\gamma}^2 + (m_{fp} + m_c + m_{sp})\ddot{x}_c + (-m_{sp}l_{sp}\cos(\alpha) - m_{fp}l_{sp}\cos(\alpha))\ddot{\alpha}$$
$$-m_{fp}l_{fp}\cos(\gamma)\dot{\gamma} = F_c$$

the second Lagrange equation is

$$(-m_{fp}l_{fp}\sin(\gamma)l_{sp}\cos(\alpha) + m_{fp}l_{fp}\cos(\gamma)l_{sp}\sin(\gamma))\dot{\gamma}^2 + (-m_{sp}l_{sp}\cos(\alpha) - m_{fp}l_{sp}\cos(\alpha))\ddot{x}_c + (J_{sp}$$
$$+m_{fp}l_{sp}^2 + m_{sp}l_{sp}^2)\ddot{\alpha} + (m_{fp}l_{fp}\sin(\gamma)l_{sp}\sin(\alpha) + m_{fp}l_{fp}\cos(\gamma)l_{sp}\cos(\alpha))\ddot{\gamma} - m_{sp}gl_{sp}\sin(\alpha) - m_{fp}gl_{sp}\sin(\alpha) = 0$$

the third Lagrange equation is

$$K_s\gamma + (-m_{fp}l_{fp}\cos(\gamma)l_{sp}\sin(\alpha) + m_{fp}l_{fp}\sin(\gamma)l_{sp}\cos(\alpha))\dot{\alpha}^2 - m_{fp}l_{fp}\cos(\gamma)\ddot{x}_c + (m_{fp}l_{fp}\sin(\gamma)l_{sp}\sin(\alpha)$$
$$+m_{fp}l_{fp}\cos(\gamma)l_{sp}\cos(\alpha))\ddot{\alpha} + (J_{fp} + m_{fp}l_{fp}^2)\ddot{\gamma} - m_{fp}gl_{fp}\sin(\gamma) = 0$$

Solving the two Lagrange equations for the second-order time derivative of the Lagrangian coordinates results in the non-linear equations presented in the *FLEXPEN.mws* Maple^{TM} worksheet, or the HTML equivalent.

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

$$F_c = \frac{\eta_g K_g K_t}{R_m r_{mp}}\left(-\frac{K_g K_m \dot{x}_c}{r_{mp}} + \eta_m V_m\right) \tag{2.4}$$

See [1] 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

$$\dot{x} = Ax + Bu \tag{2.5}$$

and

$$y = Cx + Du \tag{2.6}$$

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

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

and

$$y^\top = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}.$$

After linearizing the nonlinear equations of motion about the zero angle (balanced) position, and substituting the state given in Equation 2.1.4, we obtain the state-space matrices presented in the *FLEXPEN.mws* Maple^{TM} worksheet, or the HTML equivalent.

Note: The velocities of the servo and pendulum angles 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 Flexible Pendulum 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 ([5]):

- 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

$$\det\left(sI - A\right) = 0 \tag{2.7}$$

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 $i = 1 \ldots n$, from an initial state to a final state then the system is controllable, otherwise it is uncontrollable ([5]).

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

$$T = \begin{bmatrix} B & AB & A^2B & \ldots & A^nB \end{bmatrix} \tag{2.8}$$

equals the number of states in the system,

$$\text{rank}(T) = n. \tag{2.9}$$

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 2.5, find a control input u that minimizes the cost function

$$J = \int_0^\infty x(t)'Qx(t) + u(t)'Ru(t)\, dt, \tag{2.10}$$

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 2.5 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 control the position of the IP02 linear cart while balancing the rigid and flexible pendulums.

The reference state is defined

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

The controller is therefore

$$u = -Kx, \tag{2.11}$$

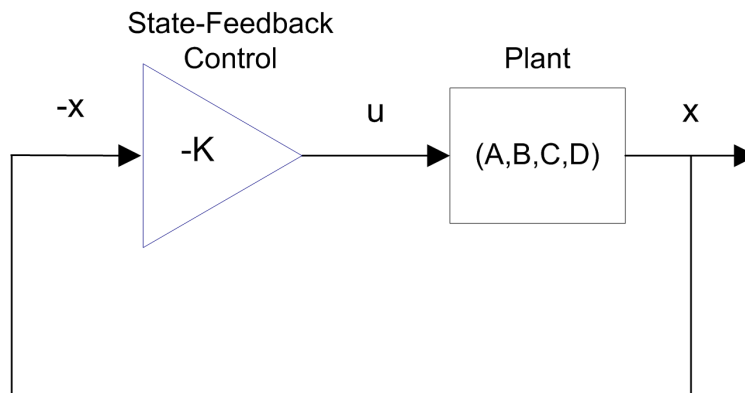which is the controller used in the LQR algorithm.

Figure 2.2: State-feedback control loop

To eliminate linear cart regulation 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

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

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

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

to help compensate for unmodeled dynamics in the actual system that cause the cart to drift from its desired postiion.

3 LAB EXPERIMENTS

3.1 Simulation

In this section we will use the VI shown in Figure 3.1 to simulate the closed-loop control of the Flexible Pendulum system. The system is simulated using the linear model summarized in Section 2.1. The VI uses the state-feedback control described in Section 2.2.4. The feedback gain K is found using the LQR command from the *Control Design and Simulation Toolkit* (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.
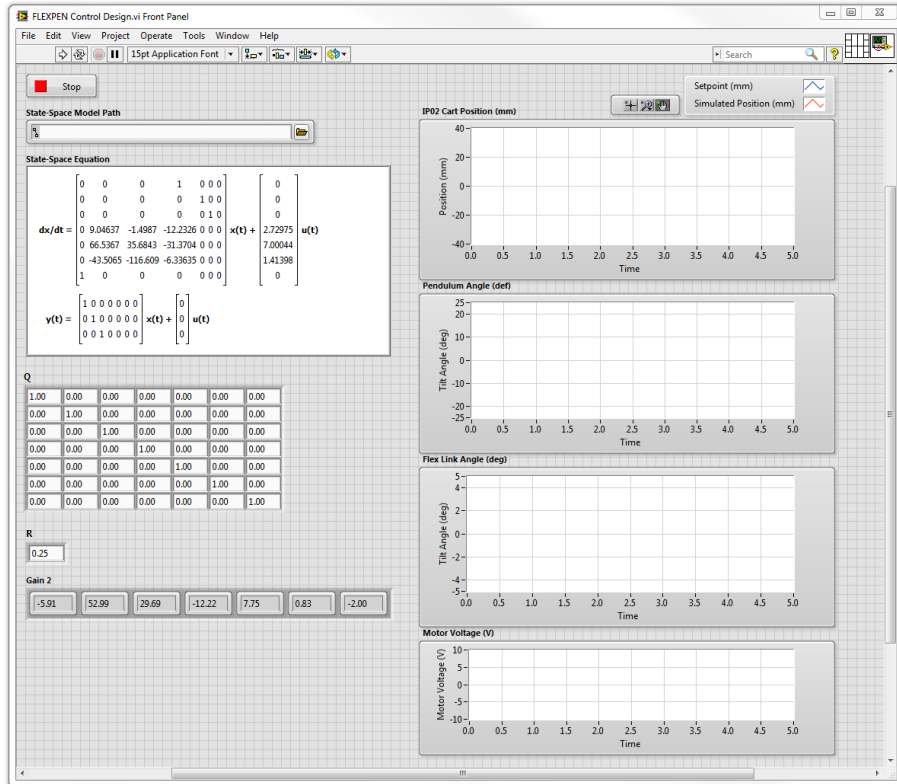

Figure 3.1: VI used to simulate Flexible Pendulum.

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. Open and run *FLEXPEN Control Design.vi* as described in Section 4. Make sure you choose your model file using the *Model Path* control. The model file is generated using the *FLEXPEN Modeling* VI by entering the state space model and exporting the resultant model file.

2. By default, the Q matrix is sent to identity matrix. Set the LQR weighting matrices to

$$Q = \begin{bmatrix} 50 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \end{bmatrix}$$

and

$$R = 1.$$

3. This automatically generates the gain

$$K = \begin{bmatrix} -7.92 & 43.69 & 10.87 & -13.43 & 7.22 & 1.82 & -0.71 \end{bmatrix}.$$

LQR Tuning: When tuning the LQR, we start with the identity matrix. To put more emphasis on the response of the linear cart, we set the cart position gain $Q(1,1)$ = 50, and the derivative term $Q(4,4)$ = 10. The last diagonal element, $Q(7,7)$ is set to 0.5 to generate an integral gain for the linear cart to keep it centered on the track.

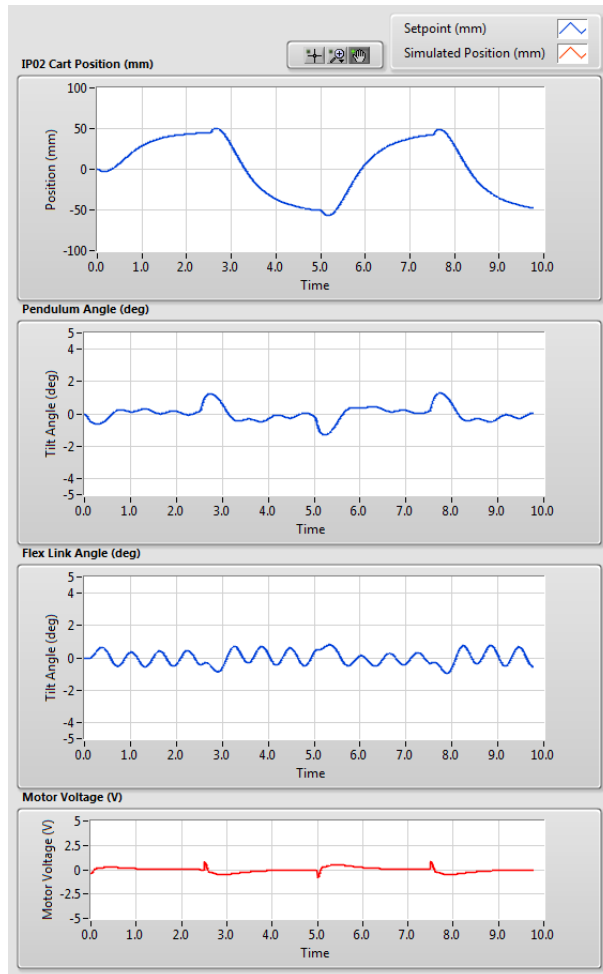4. Run the VI. The scopes should be displaying responses similar to Figure 3.2.

Figure 3.2: Simulated closed-loop response.

5. Click on the *STOP* button to stop running the VI.

3.1.2 Analysis

As shown by the response in Figure 3.2, the pendulums maintain their balanced positions despite the applied 50 mm cart position disturbance. Further analysis can be performed using the *Graph Palette*.

3.2 Implementation

The *FLEXPEN Balance Control* VI shown in Figure 3.3 is used to perform the balance control on the FLEXPEN. The VI contains Quanser Rapid Control Prototyping Toolkit® blocks that interface with the dc motor and sensors of the FLEXPEN system.
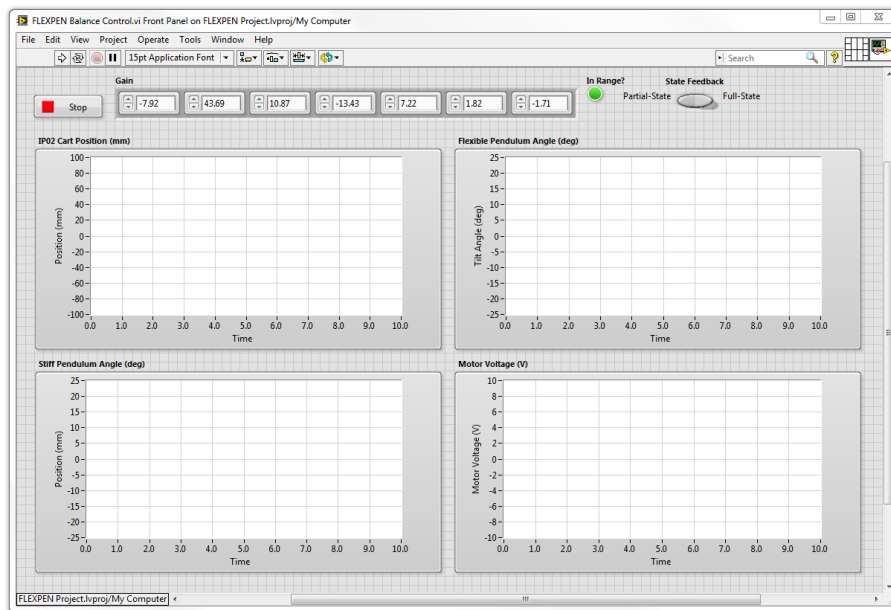

Figure 3.3: VI used to run controller on the FLEXPEN.

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. Make sure gain K is set to the gain you found and simulated in Section 3.1.

2. **Make sure that the cart is close to the centre of the track and the pendulums are completely still.**

3. Check that the *State Feedback* switch is set to *Full-State*.

4. Run the VI.

5. Once the controller is running, slowly raise the pendulums counter-clockwise (CCW) to their upright vertical position. You should feel the motor voltage kick-in when it is within the range where the balance control engages. The scopes should be displaying responses similar to Figure 3.4.

Note: Once the controller has engaged, do not attempt to manually lower the pendulums. If the pendulums or carts move outside of a safe workspace, the system watchdog should halt the controller automatically.
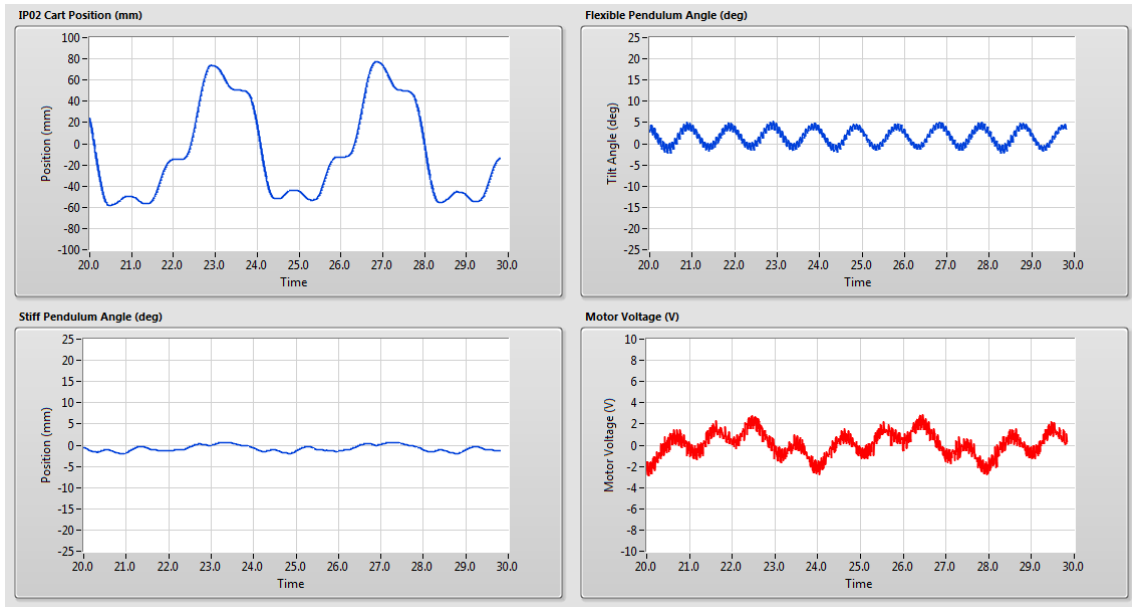

Figure 3.4: Typical response when balancing the FLEXPEN system

6. To stop the experiment, click on the *Stop* button but **make sure you catch the pendulums before they swing down**.

3.2.2 Analysis

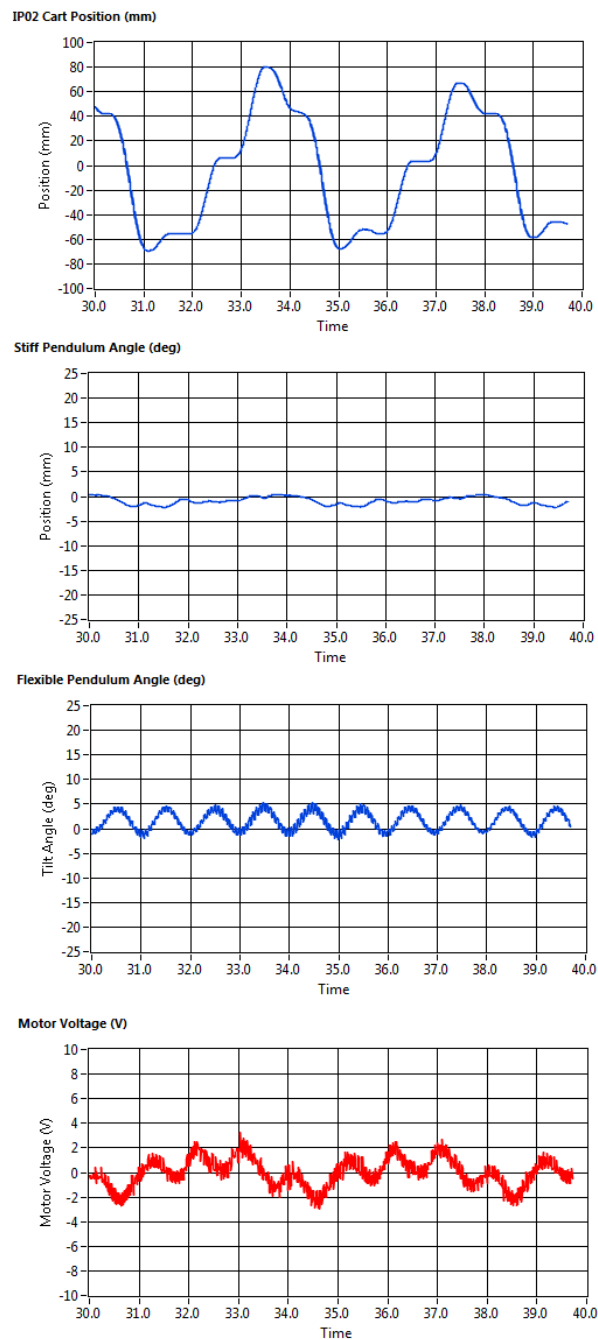An example of the balance control response is shown in Figure 3.5.

Figure 3.5: FLEXPEN balance control response

Due to the friction in the system, the IP02 servo oscillates back-and-forth approximately ±70 mm to balance the pendulum. The pendulum angle does not exceed 3 degrees and the flexible link angle does not exceed 5 degrees when balanced. Because of the integrator, the IP02 cart eventually returns to the initial 0 mm setpoint.

3.2.3 Partial-State Feedback

1. **Make sure that the cart is close to the centre of the track and the pendulums are completely still.**

2. Check that the *State Feedback* switch is set to *Full-State*.

3. Run the VI.

4. Once the controller is running, slowly raise the pendulums counter-clockwise (CCW) to their upright vertical position. You should feel the motor voltage kick-in when it is within the range where the balance control engages.

5. Once the response of the pendulums is stable, set the *State Feedback* switch to *Partial-State*.

6. Introduce a slight disturbance into the pendulums and observe the response of the system. The system should begin to oscillate with an increasing amplitude as shown in Figure 3.6.

7. **Do not leave the switch on *partial-state feedback* for more than a few seconds**. Once you have observed the system response, set the manual switch back to *full-state feedback*.
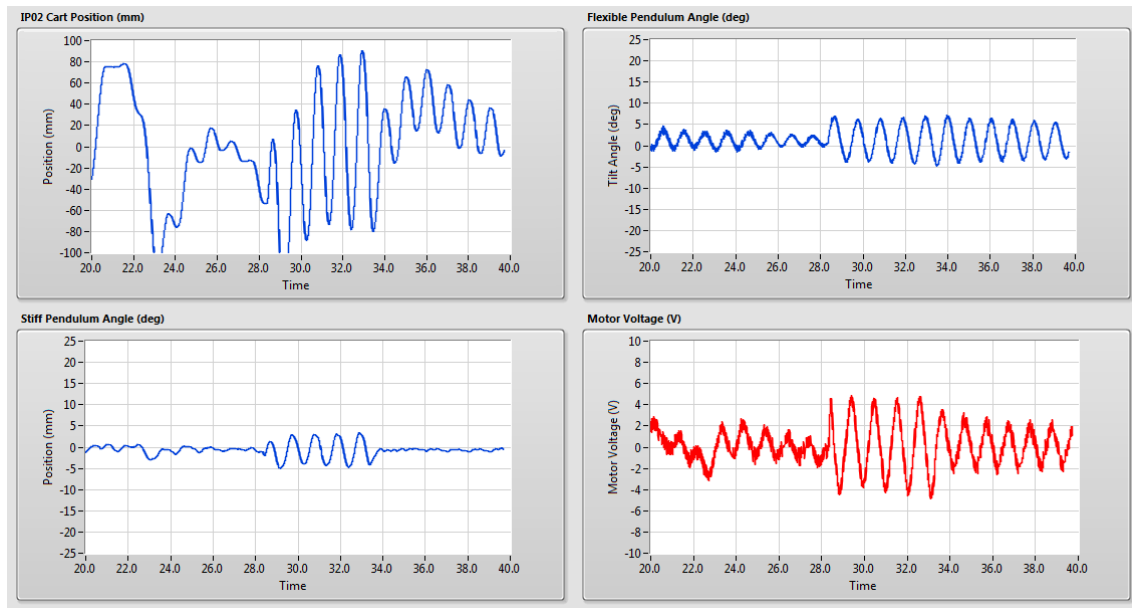

Figure 3.6: Typical partial-state feedback response when balancing the FLEXPEN system

8. Observe the response of the system once *full-state* feedback is re-engaged (shown in Figure 3.6 at 34 seconds).

9. To stop the experiment, click on the *Stop* button but **make sure you catch the pendulums before they swing down**.

3.2.4 Analysis

An example of the closed-loop balance response under partial-state feedback is shown in Figure 3.5.
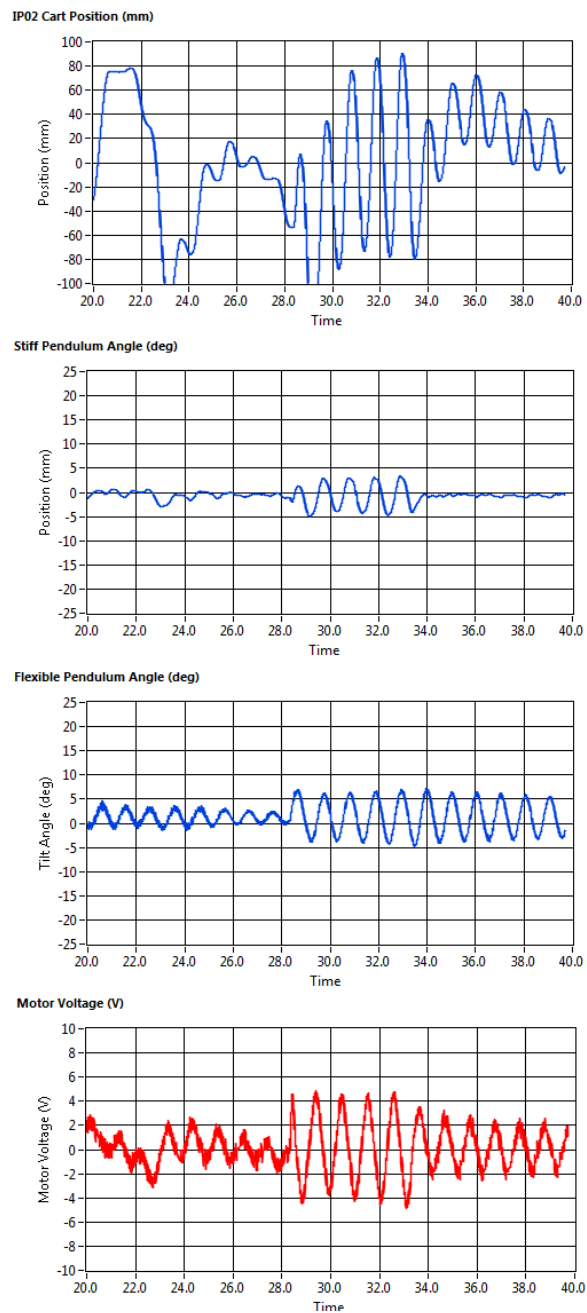
Figure 3.7: Typical partial-state feedback response when balancing the FLEXPEN system

If the flexible link is moving "in-synch" with the stiff pendulum then the system may remain stable even when using partial-state feedback. However when a disturbance is applied (shown in Figure 3.7 at 29 seconds), the stiff and flexible pendulum angles begin to oscillate with increasing amplitude as shown in Figure 3.7. Though stability can sometimes be restored under partial-state feedback, the system response is far less robust than when full-state feedback is engaged since the flexible link angle is not being fed back into the control system. Once the angle of the flexible pendulum is reintroduced (shown in Figure 3.7 at 34 seconds), the oscillations in the cart position and stiff pendulum angle are damped out quite quickly.

4 SYSTEM REQUIREMENTS

Required Software

Make sure LabVIEW^{TM} is installed with the following required add-ons:

1. LabVIEW^{TM}

2. NI-DAQmx

3. NI LabVIEW^{TM} Control Design and Simulation Module

4. NI LabVIEW^{TM} MathScript RT Module

5. Quanser Rapid Control Prototyping Toolkit®

Note: Make sure the Quanser Rapid Control Prototyping (RCP) Toolkit is installed after LabVIEW. See the RCP Toolkit Quick Start Guide for more information.

Required Hardware

- Data acquisition (DAQ) device **with 2x encoder inputs** and that is compatible with Quanser Rapid Control Prototyping Toolkit®.

- Quanser IP02 linear servo.

- Quanser Flexible Pendulum (positioned underneath the IP02).

- Quanser VoltPAQ-X1 power amplifier, or equivalent.

Before Starting Lab

Before you begin this laboratory make sure:

- LabVIEW^{TM} is installed on your PC.

- DAQ device has been successfully tested (e.g., using the test software in the Quick Start Guide or the *Analog Loopback Demo*).

- Flexible Pendulum and amplifier are connected to your DAQ board as described its User Manual [3].

4.1 Overview of Files

File Name	Description
Flexible Pendulum User Manual.pdf	This manual describes the hardware of the FLEXPEN system and explains how to setup and wire the system for the experiments.
Flexible Pendulum Laboratory Manual.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 FLEXPEN plant using LabVIEW™ .
FLEXPEN Project.lvproj	LabVIEW project that contains all the VIs required for the lab.
FLEXPEN Modeling.vi	VI used to generate the linear state-space model of the FLEXPEN system.
FLEXPEN Control Design.vi	VI used to design the LQR state-feedback gain and simulate the FLEXPEN system.
FLEXPEN Balance Control.vi	VI that implements the state-feedback control on the FLEXPEN system.
FLEXPEN.mws	Maple worksheet used to develop the model for the FLEXPEN experiment. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
FLEXPEN.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 FLEXPEN

4.2 Setup for Simulation

Before beginning the in-lab procedure outlined in Section 3.1, the modeling and control design VIs must must be configured.

Follow these steps:

1. Load LabVIEW™ .

2. Open the *FLEXPEN Project.lvproj* LabVIEW project, shown in Figure 4.1.

3. Open the *FLEXPEN Modeling.vi* shown in Figure 4.2.

4. The pendulum and IP02 parameters are already set, by default. Run the VI to generate the linear state-space model.

5. In *Model Name*, enter the name of the model you and click on OK. This will save the state-space model under the folder *Model Files*. You can close this VI now.

6. Open the *FLEXPEN Control Design* VI, shown in Figure 3.1.

7. Using the *File Path* control, select the model file.

8. Run the VI. The state-space model should load. You are now ready to design your LQR control and simulate the closed-loop response.
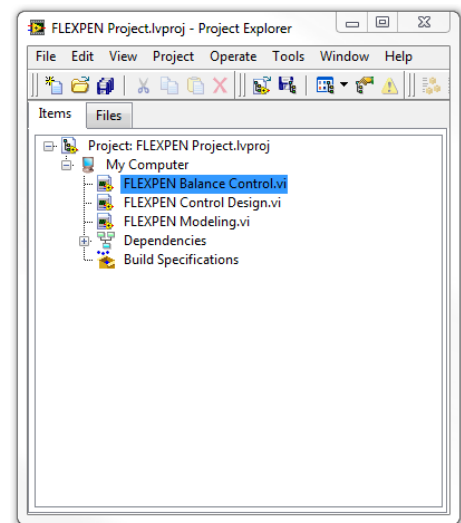

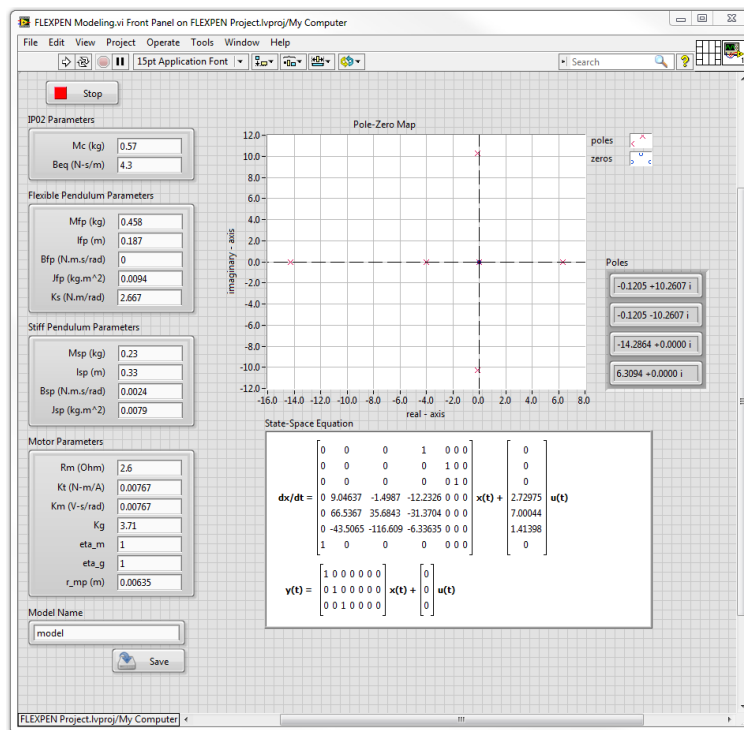Figure 4.1: LabVIEW Flexible Pendulum Project

Figure 4.2: Flexible Pendulum Modeling VI

4.3 Setup for Running on FLEXPEN

Before performing the in-lab exercises in Section 3.2, the FLEXPEN system and the *FLEXPEN Balance Control.vi* must be configured properly.

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

1. Setup the IP02 with the FLEXPEN module as detailed in the FLEXPEN User Manual [3].

2. **Make sure that the cart is close to the centre of the track and the pendulums are completely still.**. For more information, go to the FLEXPEN User Manual [3].

3. Open the *FLEXPEN Balance Control.vi*, shown in Figure 3.3.

4. Set gain *K* control in the VI to the value found in Section 4.2 (or another gain you want to test on the system).

5. **Configure DAQ:** Ensure the HIL Initialize block is configured for the DAQ device that is installed in your system. To do this, go to the block diagram (CTRL-E) and double click on the **HIL Initialize** Express VI shown in Figure 4.3.
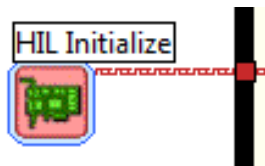

Figure 4.3: HIL Initialize Express VI

6. Under the Main tab, select the data acquisition device that is installed on your system in the *Board type* section. For example, in Figure 4.4 the Q2-USB is chosen.
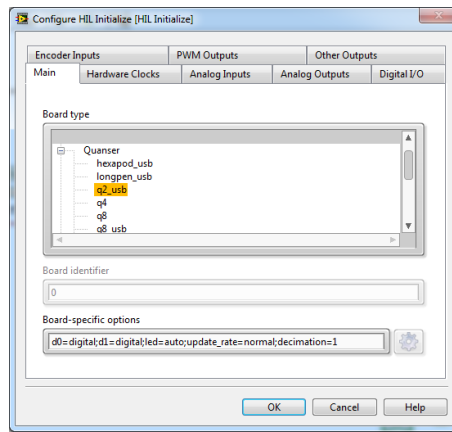
Figure 4.4: Select DAQ board that will be used to control system

REFERENCES

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

[2] Quanser Inc. *SIP and SPG User Manual*, 2009.

[3] Quanser Inc. *FLEXPEN User Manual*, 2012.

[4] Quanser Inc. *IP02 Lab Workbook (LabVIEW)*, 2012.

[5] 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**

▶ **Linear Flexible Inverted Pendulum**

▶ **Linear Pendulum**

▶ **Linear Double Inverted Pendulum**

▶ **Linear Flexible Joint**

▶ **Linear Flexible Joint with Inverted Pendulum**

▶ **Seesaw**

▶ **Seesaw Pendulum**

▶ **Linear Flexible Joint on Seesaw**

Quanser's linear collection allows you to create experiments of varying complexity – from basic to advanced. With nine plants to choose from, students can be exposed to a wide range of topics relating to mechanical and aerospace engineering. For more information please contact info@quanser.com

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