# STUDENT WORKBOOK

## Ball and Beam Experiment for MATLAB®/Simulink® Users

Standardized for ABET* Evaluation Criteria

Developed by:
Jacob Apkarian, Ph.D., Quanser
Michel Lévis, M.A.Sc., Quanser
Hakan Gurocak, Ph.D., Washington State University

SRV02 educational solutions are powered by: MATLAB SIMULINK

Course material complies with: ABET

CAPTIVATE. MOTIVATE. GRADUATE.

*ABET Inc., is the recognized accreditor for college and university programs in applied science, computing, engineering, and technology. Among the most respected accreditation organizations in the U.S., ABET has provided leadership and quality assurance in higher education for over 75 years.

# Acknowledgements

Quanser, Inc. would like to thank the following contributors:
Dr. Hakan Gurocak, Washington State University Vancouver, USA, for his help to include embedded outcomes assessment, and
Dr. K. J. Åström, Lund University, Lund, Sweden for his immense contributions to the curriculum content.

# 1 Modeling

## 1.1 Background

### 1.1.1 Nonlinear Equation of Motion

The free body diagram of the Ball and Beam is illustrated in Figure 1.1. Using this diagram, the equation of motion (EOM) relating the motion of the ball, $x$, to the angle of the beam, $\alpha$, can be found. Based on Newton's First Law of Motion, the sum of forces acting on the ball along the beam equals

$$m_b\ddot{x}(t) = \sum F = F_{x,t} - F_{x,r} \tag{1.1}$$

where $m_b$ is the mass of the ball, $x$ is the ball displacement, $F_{x,r}$ is the force from the ball's inertia, and $F_{x,t}$ is the translational force generated by gravity. Friction and viscous damping are neglected.

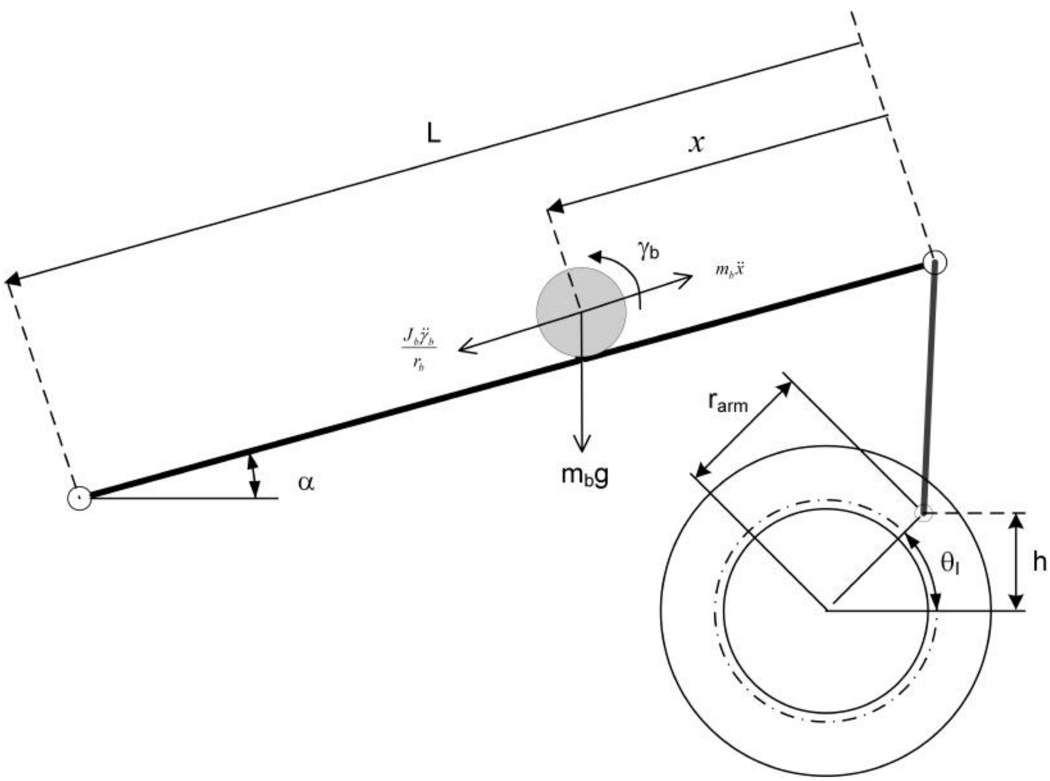



Figure 1.1: Free-body diagram of Ball and Beam.

**Modeling Conventions**:

- Applying a positive voltage causes the servo load gear to move in the positive, counter-clockwise (CCW) direction. This moves the beam upwards and causes the ball to roll in the positive direction (i.e. away from the servo towards the left). Thus $V_m > 0 \rightarrow \dot{\theta}_l > 0 \rightarrow \dot{x} > 0$.
- Ball position is zero, $x = 0$, when located in the center of the beam.
- Servo angle is zero, $\theta_l = 0$, when the beam is parallel to the ground, $\alpha = 0$.

For the ball to be stationary at a certain moment, i.e. be in equilibrium, the force from the ball's momentum must be equal to the force produced by gravity. The force caused by the rotation of the ball is

$$F_{x,r} = \frac{\tau_b}{r_b} \tag{1.2}$$

where $r_b$ is the radius of the ball and for an angular ball position $\gamma_b$ the torque equals

$$\tau_b = J_b \ddot{\gamma}_b(t).$$

Applying the sector formula we can convert between linear and angular displacement and get $x(t) = \gamma_b(t)\, r_b$. The force acting on the ball in the $x$ direction from its momentum in (Equation 1.2) becomes

$$F_{x,r} = \frac{J_b\, \ddot{x}(t)}{r_b^2}. \tag{1.3}$$

The gravitational force acting on the ball in the $x$ direction can be found from Figure 1.1.

### 1.1.2 Relative to Servo Angle

In order to relate the ball position to the servo angle (as opposed to the beam angle) we need to find the relationship between the Rotary Servo load gear angle, $\theta_l$, and the beam angle, $\alpha$. Using the schematic given in Figure 1.1, consider the beam and servo angles required to change the height of the beam by $h$. Taking the sine of the beam angle gives the expression

$$\sin \alpha(t) = \frac{h}{L} \tag{1.4}$$

and taking the sine of the servo load shaft angle results in the equation

$$\sin \theta_l(t) = \frac{h}{r_{arm}} \tag{1.5}$$

### 1.1.3 Obtaining Transfer Function

As illustrated in Figure 1.2, this system is comprised of two plants: the Rotary Servo and the Ball and Beam.

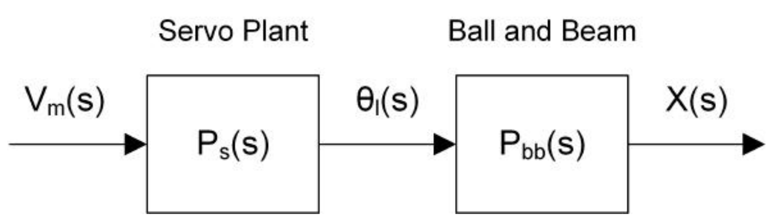



Figure 1.2: Ball and Beam open-loop block diagram.

The complete system transfer function is

$$P(s) = P_{bb}(s) P_s(s). \tag{1.6}$$

The Ball and Beam transfer function

$$P_{bb}(s) = \frac{X(s)}{\Theta_l(s)} \tag{1.7}$$

describes the linear displacement of the ball, $x(t)$, with respect to the load angle of the servo, $\theta_l(t)$.

The Rotary Servo transfer function

$$P_s(s) = \frac{\Theta_l(s)}{V_m(s)} \tag{1.8}$$

models the servo load gear position, $\theta_l(t)$, with respect to the servo input voltage, $V_m(t)$. This transfer function was found to be:

$$P_s(s) = \frac{K}{s(\tau s + 1)} \tag{1.9}$$

where $K = 1.5$ rad/s/V is the model steady-state gain and $\tau = 0.025$ s is the model time constant. If desired, you can conduct an experiment to find more precise model parameters, $K$ and $\tau$, for your particular servo. See Rotary Servo Modeling laboratory experiment for more information.

## 1.2 Pre-Lab Questions

1. Find the gravitational force acting on the ball in the $x$ direction, $F_{x,t}$.
2. Obtain the nonlinear equation of motion. This equation should be in the form: $\ddot{x} = f(\alpha)$.
3. Find the moment of inertia of the ball based on its mass, $m_b$, and radius, $r_b$. Apply it to the equation of motion found and simplify the expression. If the ball doubled in size and mass, how would it affect the equation?
4. Relate the equation of motion to the servo angle, $\theta_l$.
5. Linearize the equation of motion about the servo angle $\theta_l(t) = 0$ . Lump the coefficient parameters of $\theta_l(t)$ into parameter $K_{bb}$ - the *model gain* of the Ball and Beam system. Evaluate the gain given beam length of 16.75 inches and arm radius of 1 inch.
6. Find the transfer function, $P(s)$, of the complete Ball and Beam system that represents the position of the ball with respect to the input motor voltage of the servo. Assume all initial conditions are zero.

## 1.3 In-Lab Exercises

Based on the models already designed in SRV02 QUARC Integration, design a model that also reads the ball position similar as shown in Figure 1.3. Follow the setup and wiring procedure in the Ball and Beam User Manual. With the default wiring, the ball potentiometer can be read on analog input channel #0. Set the *Ball Sensor Gain* block to 1 to output voltage.

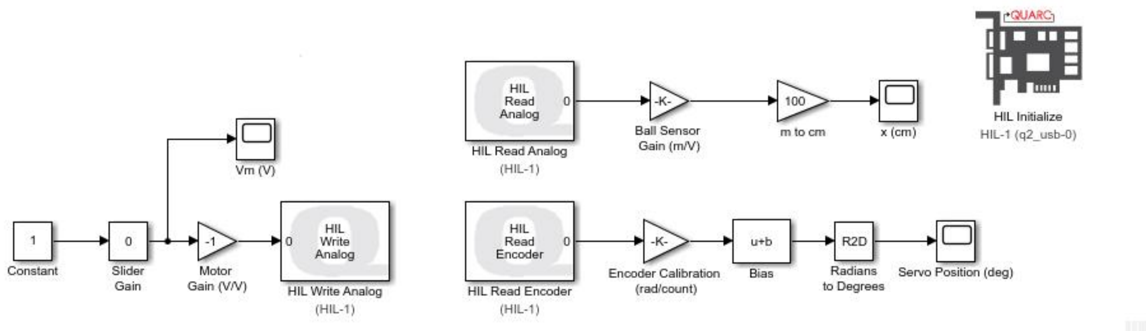



Figure 1.3: Measuring servo and ball position

1. Build and run the QUARC controller. Make sure 0 V is applied to the servo.
2. The potentiometer outputs a $\pm 5$ V signal proportional to the position of the ball. To confirm this, move the ball along the beam and examine the voltage. Record what voltage is being measured at the left and right limits as well as in the center.
3. Determine the sensor gain required to measure the position of the ball *in meters* and according to the model convention shown in Figure 1.1. The beam is 16.75 inches long.
4. Enter the sensor gain you found in the *BB01 Sensor Gain*. Move the ball from end-to-end. Make sure the ball position measurement is as expected (i.e. follows the modeling conventions). Attach a response of the ball moving along the beam from right to left, i.e. away from the servo.
5. Make sure the servo voltage and angle measurement follow the model conventions. Modify the Simulink diagram if necessary. For the test, slowly increase the *Slider Gain* until enough voltage is supplied to rotate the servo. Initially, it is recommended to disconnect the Ball and Beam module prior to doing this to make sure the servo rotates in the expected direction. Attach responses showing the voltage, servo angle, and ball position when a positive voltage is applied. Record any actuator and sensor gains used and give briefly explain why the gains had to be set to those value.
6. Stop the QUARC controller.
7. Shut off the power amplifier is no more experiments are to be performed in this session.

## 1.4 Results

Fill out Table Table 1.1 below with your answers to the Pre-Lab questions and your results from the lab experiments.

| Section / Question | Description | Symbol | Value | Unit |
|---|---|---|---|---|
| Section 1.2, Question 5 | Open-loop model gain | $K_{bb}$ | | m/rad |
| Section 1.3, Question 3 | Sensor gain | $K_{bs}$ | | m/V |

Table 1.1: Summary of results for the Ball and Beam modeling laboratory.

# 2 Control Design and Simulation

## 2.1 Background

### 2.1.1 Model

The Ball and Beam modeling was performed in Section 1. In summary the resulting the transfer function describing the position of the ball, $x$, relative to the servo angle, $\theta_l$, is

$$P_{bb}(s) = \frac{X(s)}{\Theta_l(s)} = \frac{K_{bb}}{s^2} \tag{2.1}$$

The Rotary Servo transfer function models the servo load gear position, $\theta_l(t)$, with respect to the servo input voltage, $V_m(t)$. This transfer function was found to be:

$$P_s(s) = \frac{\Theta_l(s)}{V_m(s)} = \frac{K}{s(\tau s + 1)} \tag{2.2}$$

where $K = 1.5$ rad/s/V is the model steady-state gain and $\tau = 0.025$ s is the model time constant. If desired, you can conduct an experiment to find more precise model parameters, $K$ and $\tau$, for your particular servo. See Rotary Servo Modeling laboratory experiment laboratory for more information.

### 2.1.2 Specifications

The steady-state error, 4% settling time, and percentage overshoot specifications for controlling the position of the ball are:

$$|e_{ss}| \leq 0.5 \text{ cm} \tag{2.3}$$

$$t_s \leq 3.0 \text{ s} \tag{2.4}$$

$$PO \leq 5.0 \text{ \%} \tag{2.5}$$

Thus, given a step reference, the peak position of the ball (i.e. percentage overshoot) should not exceed 5%. After 3.0 seconds, the ball should settle within 4% of its steady-state value (i.e. not the reference) and the steady-state should be within 5 mm of the desired position.

For a second-order under damped system, the settling time and percent overshoot equations are

$$t_s = -\frac{\ln\left(c_{ts}\sqrt{1-\zeta^2}\right)}{\zeta\,\omega_n} \tag{2.6}$$

and

$$PO = 100 e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}} \tag{2.7}$$

where $\omega_n$ is the natural frequency $\zeta$ is the damping ratio.

### 2.1.3 Control Design

The control that will be used for the Ball and Beam system is illustrated by the block diagram in Figure 2.1. Based on the measured ball position $X(s)$, the outer ball control loop computes the servo load shaft angle $\Theta_d(s)$ to attain the desired ball position $X_d(s)$. The inner loop controls the servo position using a proportional gain $k_{p,s}$.

To design the ball position control, assume that the inner servo loop is ideal and therefore

$$\theta_l(t) = \theta_d(t) \tag{2.8}$$

As shown in the block diagram, the outer-loop is a PD control in the form

$$\Theta_d(s) = K_c(s+z)(X_d(s) - X(s)) \tag{2.9}$$

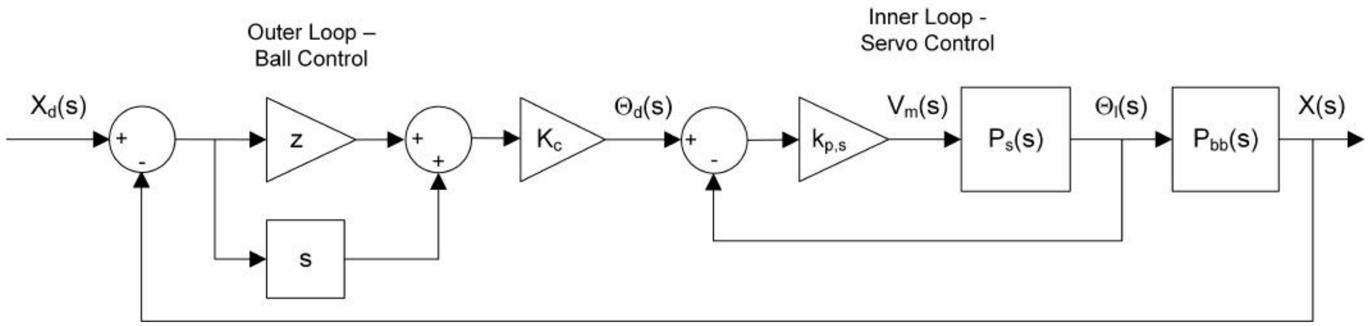



Figure 2.1: Control system for Ball and Beam

where $K_c$ is the compensator proportional gain and $z$ is the zero location.

Given the assumption that $\Theta_l(t) = \Theta_d(t)$, substitute the control Equation 2.9 into the Ball and Beam plant transfer function Equation 2.1 and solve for $X(s)/X_d(s)$ to obtain the *closed-loop transfer function*

$$\frac{X(s)}{X_d(s)} = \frac{K_{bb}K_c(s+z)}{s^2 + K_{bb}K_c s + K_{bb}K_c z} \tag{2.10}$$

In Figure 2.1, $z$ and $K_c$ are the zero location and the gain for the controller, respectively. We can compute the value for $z$ to meet the settling time and overshoot specifications. Also, we can find the value of $K_c$ to satisfy a given natural frequency and damping ratio.

A standard second order system is given by the following transfer function:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{2.11}$$

By matching the coefficients of the denominator of this equation to those in Equation 2.10, we can find the expressions for $z$ and $K_c$ to meet a certain $\omega_n$ and $\zeta$:

$$z = \frac{\omega_n^2}{K_{bb}K_c} \tag{2.12}$$

and the gain must be

$$K_c = \frac{2\zeta\omega_n}{K_{bb}} \tag{2.13}$$

**Note:** The closed-loop transfer function of the Ball and Beam given in Equation 2.10 does not strictly match the prototype second-order system because it has a zero in the numerator. This will cause a slight difference in the expected behaviour. However, this is permissible given that the control design will be tested in simulation to ensure the specifications are met prior to implementing the control on the actual system.

### Adding Filtering

The position of the ball is measured using an analog sensor and it has some inherent noise. Taking the derivative of this type of signal would output results in an amplified high-frequency signal that is eventually fed back into the motor and causes a grinding noise. As illustrated by $H(s)$ in Figure 2.2, this is prevented by using a high-pass filter.

The first-order filter replaces the derivative in Figure 2.1 and has the form

$$H(s) = \frac{\omega_f s}{s + \omega_f} \tag{2.14}$$

For adequate filtering of the noise found in the linear transducer, the cutoff frequency, $\omega_f$, will be set to 5 Hz, or

$$\omega_f = 31.4 \text{ rad/s} \tag{2.15}$$

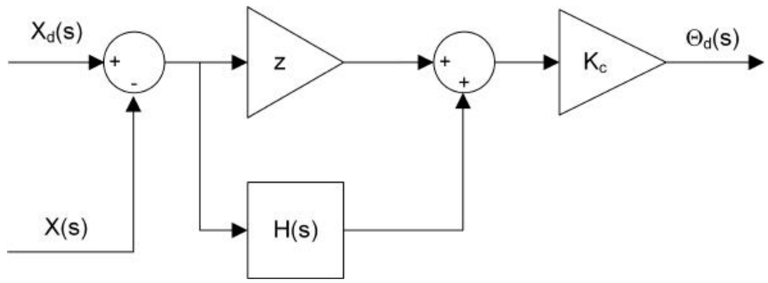



Figure 2.2: Ball and Beam control with added filtering.

## 2.2 Pre-Lab Questions

1. Consider the proportional control of the Ball and Beam shown in Figure 2.3. Find the steady-state error of the Ball and Beam when the system is controlled with the proportional control shown in Figure 2.3 and when a reference step with amplitude $R_0$ is applied

$$R(s) = \frac{R_0}{s} \tag{2.16}$$

Note that in this calculation the dynamics of the Rotary Servo are ignored and only the Ball and Beam plant is considered. Use the $P_{bb}(s)$ transfer function given in Equation 2.1.

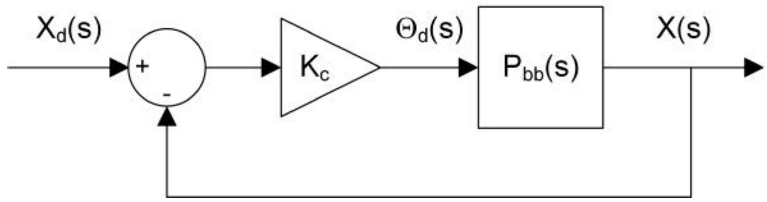



Figure 2.3: Proportional control of Ball and Beam

2. Using Figure 2.3, find the closed-loop transfer function of the Ball and Beam system with proportional control $C_{bb}(s) = K_c$.

3. Plot the root locus of the Ball and Beam forward loop plant transfer function $P_{bb}(s)$. Describe how the poles behave as $K_c$ goes to infinity.

4. Find the natural frequency and damping ratio required to achieve the time-domain specifications of the Ball and Beam plant given in Section 2.1.2.

5. After you plot the root locus of the Ball and Beam plant $P_{bb}(s)$, describe where the poles should be to satisfy the desired response specifications.

6. Discuss the response if the poles lie beyond the radius circle along the diagonal lines, i.e. away from the imaginary axis. Also, comment on what happens if the poles of the system lie inside the diagonal lines along the radius circle, i.e. moving towards the real axis. Make references to its effects on the settling time and overshoot of the response.

7. Based on the root locus obtained, can the specifications of the Ball and Beam system be satisfied using a proportional controller? Discuss.

8. Applying the PD controller $C_{bb}(s) = K_c(s + z)$ to the system as shown in Figure 2.1. Find the Ball and Beam error transfer function.

9. Find the steady-state error of the Ball and Beam closed-loop system with the *traditional* PD controller. Can the steady-state error requirement in Equation 2.3 be satisfied?

10. Based on the expressions found in Equation 2.12 and Equation 2.13, evaluate numerically the zero location and gain needed to satisfy the specifications.

# 2.3 In-Lab Exercises

The controller will be simulated before running it on the actual system. Design a SIMULINK® diagram similar as shown in Figure 2.4. This implements the control system shown in the block diagram in Figure 2.1.

- Set the servo proportional control gain to 12 V/rad.
- The ball position command is a $\pm$ 4 cm square wave at 0.05 Hz (make sure it is converted to meter for the control, as shown).
- Add a saturation block to limit the commanded servo angle from the outer-loop control to $\pm$ 56 degrees, which is the physical limit of the load gear on the actual device. **Make sure this block is set to $\pm$0.977 rad**.
- Set the simulation duration to 25 seconds.

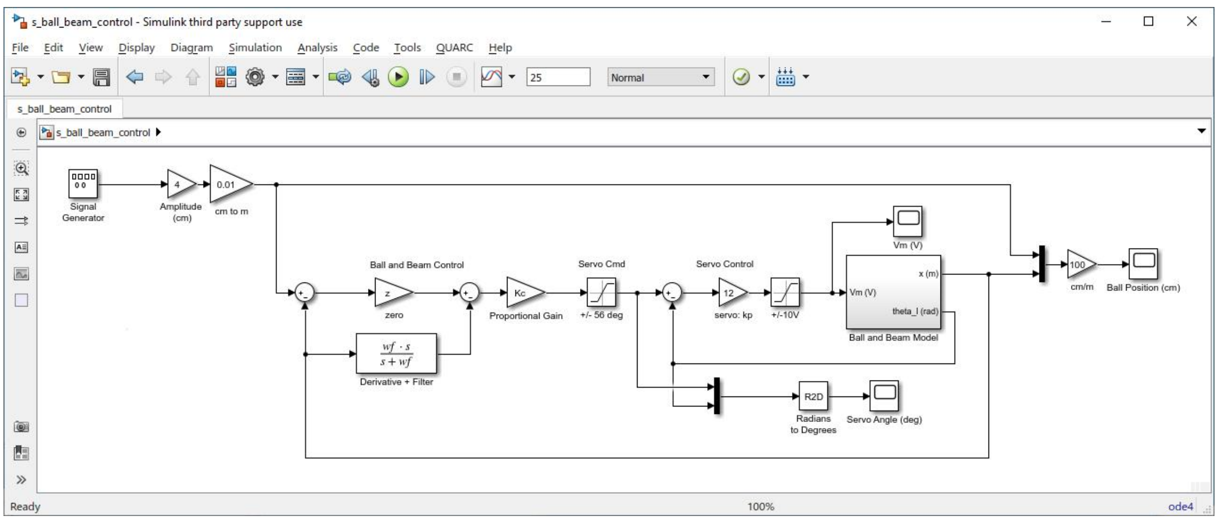



Figure 2.4: Simulink diagram used to simulate Ball and Beam system

The nonlinear model of the Ball and Beam was described in Section 1. This is implemented in the *Ball and Beam Model* subsystem shown in Figure 2.5. Notice that we are using both the Rotary Servo model and the Ball and Beam model here (i.e. not only the Ball and Beam system).

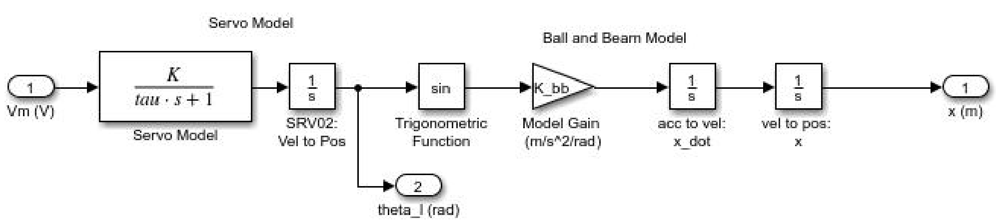



Figure 2.5: Ball and Beam Model subsystem

Simulation procedure:

1. Enter the Ball and Beam model gain found in Pre-Lab question 5 in the MATLAB® Command Window as variable *K_bb* (e.g. type K_bb = 1 in the Matlab prompt).
2. Create the open-loop transfer function of the Ball and Beam plant in MATLAB® as `P_bb`. Then enter command `sisotool(P_bb)` to load the SISO Control Design software tool. The interface should looking similar as shown in Figure 2.6.

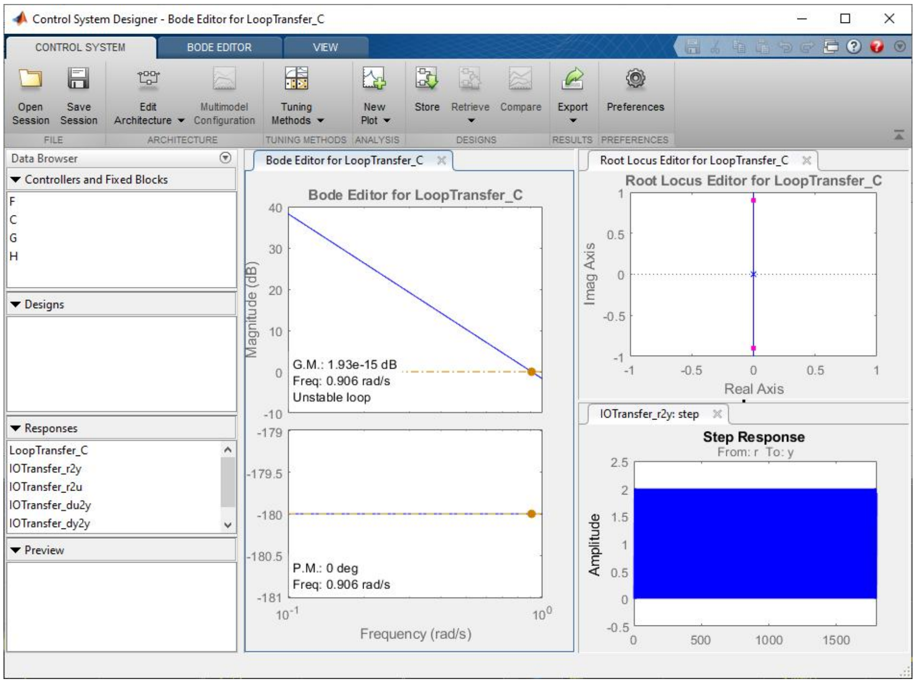



Figure 2.6: Root Locus of Open-Loop Plant

3. As shown in the *Step Response* window, the response is very oscillatory. Select the *Root Locus Editor* window and go to the *Root Locus Editor* in the toolbar. Add a zero along the real-axis in the left-hand plane. The response should change similarly as shown in Figure 2.7.

4. You can now add the control requirements by right-clicking on the *Root Locus Editor* Window and selecting *Design Requirements* | *New*. Add the *Percent Overshoot* and *Settling Time* given in Section 2.1.2. The *Root Locus Editor* with these addded requirements is shown in Figure 2.8.

5. Move the zero location and the adjust the gain by moving the poles, i.e. the red squares, until the poles are at the intersection of the settling time and percent overshoot requirements. The zero location and gain where the poles go through the desired locations should be close to what was computed in Pre-Lab question 10.

6. Run the simulation with the zero location and compensator gain found. The scope response yielded should look similar as shown in Figure 2.9. Generate a MATLAB® figure showing the ball position, servo angle, and input voltage responses.

7. Measure the steady-state error, settling time, and percent overshoot. Do they satisfy the specifications without saturating the motor, i.e. going beyond $\pm$ 10 V, or going beyond $\pm$ 56 degrees?

   **Hint:** Use the *Cursor Measurement* Tool in SIMULINK® Scope to take measurements.

8. Give a reason why the designed control gains could fail to give a successful closed-loop response on the actual system.

## 2.4 Results

Fill out Table Table 2.1 below with your answers to the Pre-Lab questions and your results from the lab experiments.

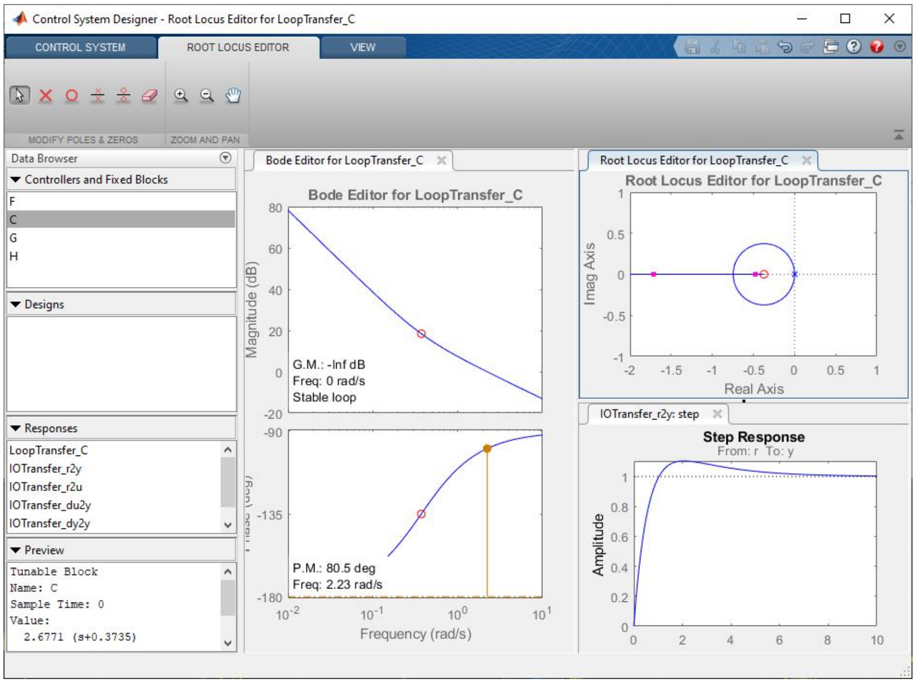



Figure 2.7: Root Locus when adding a zero to the real-axis

| **Section / Question** | **Description** | **Symbol** | **Value** | **Unit** |
|---|---|---|---|---|
| Question 10 | **Pre-Lab: PD Control Design** | | | |
| | Compensator Gain | $K_c$ | | rad/m |
| | Compensator Zero | z | | rad/s |
| Section 2.3, Step 5 | **Root Locus Control Design: SISO Tool** | | | |
| | Compensator Gain | $K_c$ | | rad/m |
| | Compensator Zero | z | | rad/s |
| Section 2.3, Step 7 | **In-Lab Simulation: PD Control** | | | |
| | Percentage overshoot | PO | | % |
| | Settling time | $t_s$ | | s |
| | Steady-state error | $e_{ss}$ | | cm |

Table 2.1: Summary of results for the Ball and Beam Control Designa and Simulation laboratory.

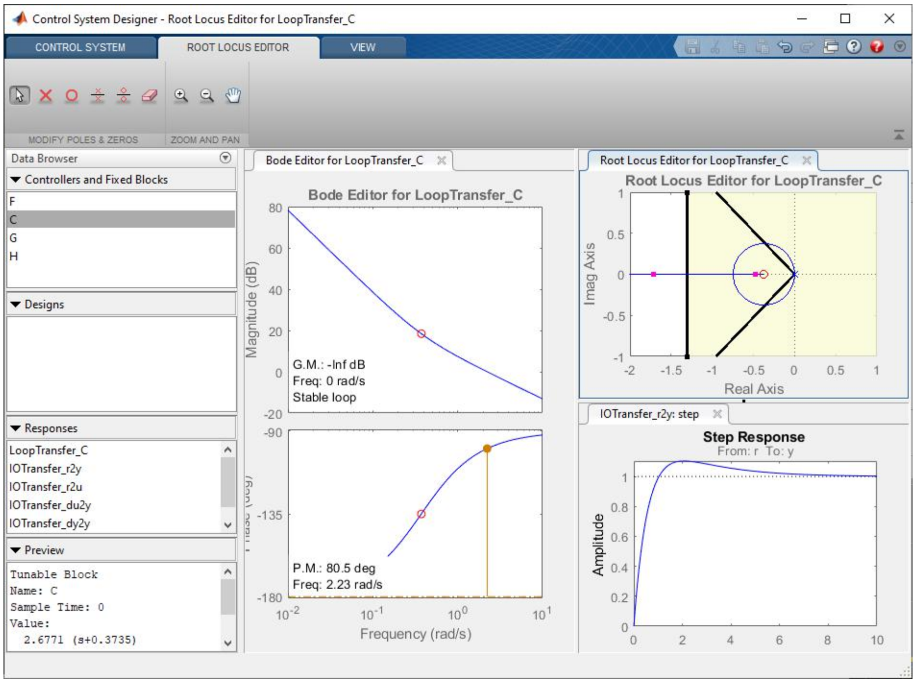
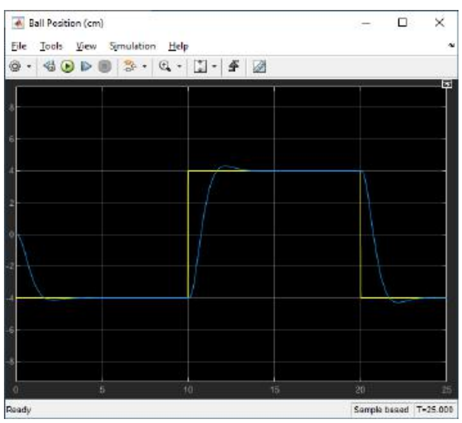
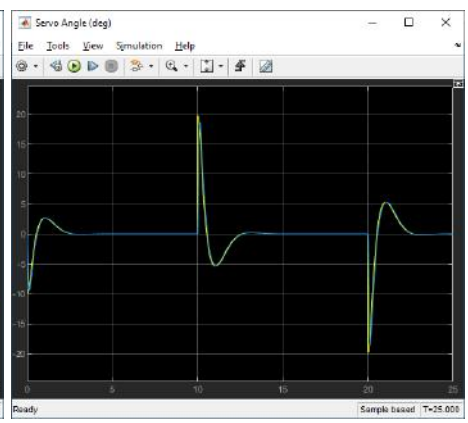


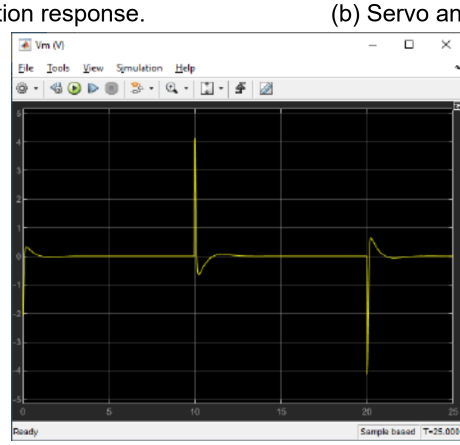
Figure 2.8: Root Locus with Percent Overshoot and Settling Time requirements added



(a) Ball position response.



(b) Servo angle response.



(c) Servo motor voltage.

Figure 2.9: Simulated ball position response of full cascade control.

# 3 Control Implementation

## 3.1 Background

In Section 2, a PD control was designed to stabilize the ball to a desired position within the specifications given in 2.1.2. For the actual Ball and Beam device, we will use the control depicted in Figure 3.1.

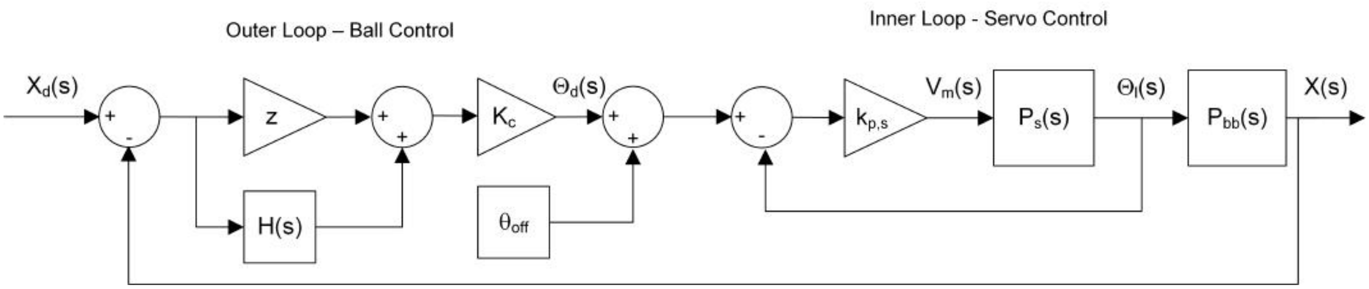



Figure 3.1: Control used in actual Ball and Beam system.

Compared to the original PD control proposed in Figure 2.2, this includes an offset adjustment for the servo angle to help eliminate the steady-state error from imprecise mechanical calibration.

**Note:** Adding an integral control to the outer-loop ball position feedback can also address this, but this often leads to undesirable overshoot and settling time.

## 3.2 In-Lab Exercises

Based on the model designed in Ball and Beam Modeling and Simulation labs in Section 1 and Section 2, respectively, design a Simulink diagram similar as shown in Figure 3.2 that implements the PD control in Figure 2.2.

**Important:** Follow the setup and wiring procedure in the Ball and Beam User Manualand **make sure the Ball and Beam system is calibrated**. The ball should be remain in the center of the beam when the servo is at angle zero.

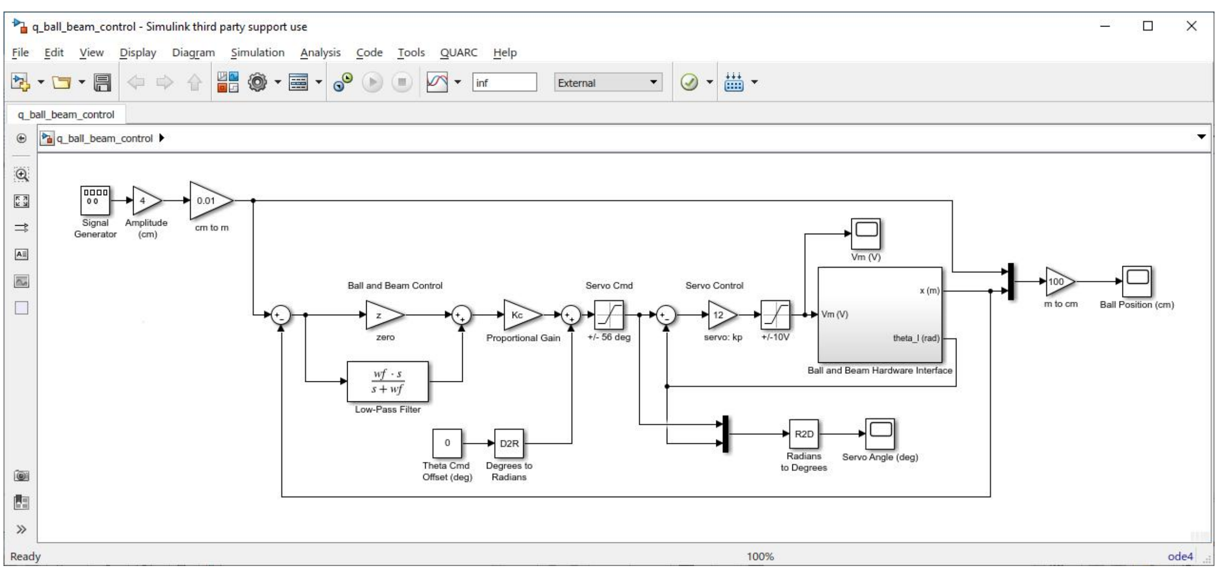
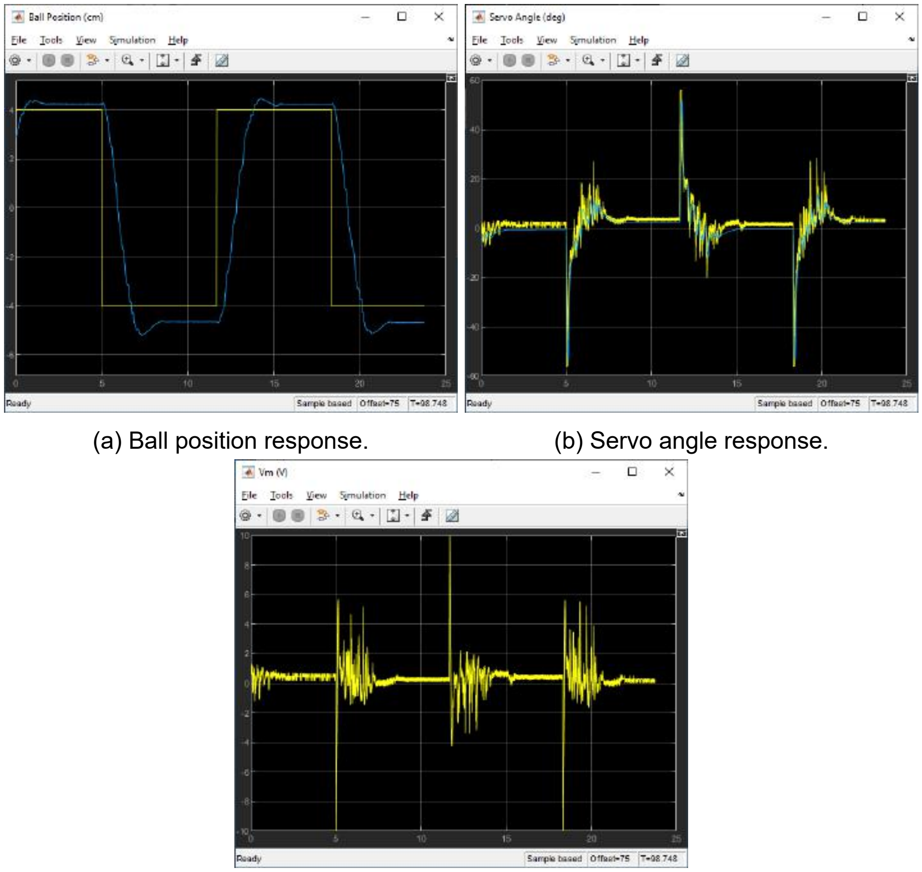



Figure 3.2: Simulink/QUARC model that implements the ball position control on Ball and Beam system

1. Build and run the QUARC controller.

2. Set the Amplitude (cm) Gain to 0 cm.
3. Run the controller with the PD gains found in Section 2 (i.e. make sure you use the final, tuned parameters). The ball should stabilize to the middle of the beam and read close to 0 cm. If not, adjust the Theta Cmd Offset block such that the ball is centered and reading 0 cm. See the sample response in Figure 3.3




(a) Ball position response.

(b) Servo angle response.

(c) Servo motor voltage.

Figure 3.3: Simulated ball position response of full cascade control.

4. Generate a MATLAB® figure showing the the ball position, servo angle, and input voltage responses.
5. Measure the steady-state error, settling time, and percent overshoot. Do they satisfy the specifications without saturating the motor, i.e. going beyond $\pm$ 10 V, or going beyond $\pm$ 56 degrees?
6. If the response did not match, tune your control gains to obtain one that matches the specifications and/or try to recalibrate the system - both mechanically and by adjusting the Theta Cmd Offset (deg). Record your new gains and briefly described the procedure used to find them. Attach the response.
7. Measure the steady-state error, settling time, and percent overshoot.
8. Stop the QUARC controller.
9. Shut off the power amplifier is no more experiments are to be performed in this session.

## 3.3 Results

Fill out Table Table 3.1 below with your answers to the Pre-Lab questions and your results from the lab experiments.

| Section / Question | Description | Symbol | Value | Unit |
|---|---|---|---|---|
| Section 3.2, step 5 | **In-Lab Implementation: PD Control** | | | |
| | Compensator Gain | $K_c$ | | rad/m |
| | Compensator Zero | z | | rad/s |
| | Servo proportional gain | $k_p$ | | V/rad |
| | Servo offset angle | $\theta_{off}$ | | deg |
| | Percentage overshoot | PO | | % |
| | Settling time | $t_s$ | | s |
| | Steady-state error | $e_{ss}$ | | cm |

Table 3.1: Summary of results for the Ball and Beam laboratory.

# 4 File Description and Configuration

## 4.1 Overview of Files

| File Name | Description |
|---|---|
| Ball and Beam Workbook (Student).pdf | Laboratory guide that contains pre-lab questions and lab experiments demonstrating how to design and implement a position controller on the Quanser Ball and Beam plant using QUARC®. |
| setup_ball_beam.m | The main MATLAB® script that sets the Ball and Beam motor and sensor parameters as well as its configuration-dependent model parameters. **Run this file only to setup the laboratory.** |
| Ball and Beam User Manual | Manual that describes the hardware of the Ball and Beam system and explains how to setup and wire the system for the experiments. |
| config_servo.m | Returns the configuration-based Ball and Beam model specifications *Rm, kt, km, Kg, eta_g, Beq, Jeq,* and *eta_m,* the sensor calibration constants K_POT and K_ENC, and the amplifier limits VMAX_AMP and IMAX_AMP. |
| config_bb.m | Returns the configuration-based BB01 model specifications L_beam, r_arm, r_b, m_b, J_b, and g, the servo offset THETA_OFF, the min/max servo limits THETA_MIN and THETA_MAX, and the sensor calibration constant K_BS. |
| q_ball_beam_interface | Simulink model that interfaces to the Ball and Beam hardware using QUARC. |
| s_ball_beam_control | Simulink file that simulates the cascade ball position controller. Both the outer-loop ball position control and the inner-loop servo position control are used in this file. |
| q_ball_beam_control | Simulink file that implements a closed-loop cascade position controller on the actual BB01 system using QUARC®. |
| calc_conversion_constants.m | Returns various conversions factors. |

Table 4.1: Files supplied with the Ball and Beam laboratory.

## 4.2 Setup for Control Simulation

Follow these steps to configure the lab properly:

1. Load the MATLAB® software.
2. Browse through the Current Directory window in Matlab and find the folder that contains the Ball and Beam controller files.
3. Double-click on the s_ball_beam_control file to open the Simulink diagram shown in Figure 2.4.
4. Double-click on the setup_ball_beam.m file to open the setup script for the Ball and Beam Simulink models.
5. Configure setup script: When used with the shortprod, the Rotary Servo must be in the high-gear configuration and no load is to be specified. Make sure the script is setup to match this configuration, i.e. the

EXT_GEAR_CONFIG should be set to 'HIGH' and the LOAD_TYPE should be set to 'NONE'. Also, ensure the ENCODER_TYPE, TACH_OPTION, K_AMP, and AMP_TYPE parameters are set according to the Rotary Servo system that is to be used in the laboratory. Next, set CONTROL_TYPE to 'MANUAL'.

6. Run the script. The following output should be see in the MATLAB® prompt:

```
Ball and Beam model parameter:
   K_bb = 1 m/s^2/rad
Ball and Beam Control Specifications:
   ts = 3 s
   PO = 5 %
Ball and Beam control:
   Kc = 0.5 s/m
   z  = 1 rad/s
   wf   = 31.4 rad/s
```

## 4.3 Setup for Control Implementation

Before beginning the in-lab exercises on the Ball and Beam device, the q_ball_beam_control SIMULINK® diagram and the setup_ball_beam.m script must be configured.

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

1. Setup the Rotary Servo with the Ball and Beam module as detailed in Ball and Beam User Manual.
2. Load the MATLAB® software.
3. Browse through the *Current Directory* window in MATLAB® and find the folder that contains the QUARC Ball and Beam control file q_ball_beam_control.
4. Double-click on the q_ball_beam_control file to open the Ball and Beam Control Simulink diagram shown in Figure 3.2.
5. **Configure DAQ:** Ensure the HIL Initialize block in the Ball and Beam Hardware Interface subsystem is configured for the DAQ device that is installed in your system. By default, the block is setup for the Quanser Q2-USB data-acquisition (DAQ) device. .
6. **Configure setup script:** Set the parameters in the setup_ball_beam.m script according to your system setup. See Section 4.2 for more details.
7. Run the script.

# 5 Lab Report

This laboratory contains three sets of experiments, namely,

1. Modeling and interfacing to hardware
2. Ball position control design and simulation
3. Ball position control implementation on actual system

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 5.4 you can find some basic tips for the *format* of your report.

## 5.1 Template for Content (Modeling)

**I. PROCEDURE**

1. *Implementation*
    - Briefly describe the main goal of lab portion of modeling the system.
    - Briefly describe the hardware interfacing procedure (Section 1.3)

**II. RESULTS**
Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 4 in Section 1.3, *Ball position response*
2. Validation of modeling conventions in step 5 in Section 1.3
3. Provide applicable data collected in this laboratory (from Table 1.1).

**III. ANALYSIS**
Provide details of your calculations (methods used) for analysis for each of the following:

1. Open-loop model gain in step 3 of Section 1.3.

**IV. CONCLUSIONS**
Interpret your results to arrive at logical conclusions for the following:

1. Whether the hardware follows the modeling conventions in step 5 in Section 1.3.

# 5.2 Template for Content (Control Design and Simulation)

### I. PROCEDURE

1. *Simulation*
   - Briefly describe the main goal of the control design and simulation.
   - Briefly describe the control design and simulation procedure (Section 2.3)

### II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 6 in Section 2.3, *Simulation of PD ball position control*
2. Provide applicable data collected in this laboratory (from Table 2.1).

### III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Open-loop root locus in step 2 of Section 2.3.
2. Resulting compensator from root locus design in step 5 of Section 2.3, *PD control designed using SISO tool*.
3. Steady state error, the settling time and percent overshoot in step 7 in Section 2.3, *Simulation of PD ball position control*
4. Reasons why the control specifications are not met in step 8 in Section 2.3

### IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in step 7 in Section 2.3, *Simulation of PD ball position control*

## 5.3 Template for Content (Control Implementation)

**I. PROCEDURE**

1. *Implementation*
    - Briefly describe the main goal of this experiment.
    - Briefly describe the experimental procedure (Section 3.2).

**II. RESULTS**

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 4 in Section 3.2, for *Implementation of PD ball position control*.
2. Response plot from step 6 in Section 3.2, for *Implementation of tuned PD ball position control*.
3. Provide applicable data collected in this laboratory (from Table 3.1).

**III. ANALYSIS**

Provide details of your calculations (methods used) for analysis for each of the following:

1. Steady state error, the settling time and percent overshoot in step 5 in Section 3.2, *Implementation of PD ball position control*.
2. Control tuning method in step 6 in Section 3.2.
3. Steady state error, the settling time and percent overshoot in step 7 in Section 3.2, *Implementation of tuned PD ball position control*.

**IV. CONCLUSIONS**

Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in step 5 in Section 3.2, *Implementation of PD ball position controller*.

## 5.4 Tips for Report Format

**PROFESSIONAL APPEARANCE**

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

Quanser Inc.
119 Spy Court
Markham, Ontario
L3R 5H6
Canada
info@quanser.com
Phone: 1-905-940-3575
Fax: 1-905-940-3576

Printed in Markham, Ontario.

For more information on the solutions Quanser Inc. offers, please visit the web site at:
http://www.quanser.com



**Waste Electrical and Electronic Equipment (WEEE)**

This symbol indicates that waste products must be disposed of separately from municipal household waste, according to Directive 2002/96/EC of the European Parliament and the Council on waste electrical and electronic equipment (WEEE). All products at the end of their life cycle must be sent to a WEEE collection and recycling center. Proper WEEE disposal reduces the environmental impact and the risk to human health due to potentially hazardous substances used in such equipment. Your cooperation in proper WEEE disposal will contribute to the effective usage of natural resources. For information about the available collection and recycling scheme in a particular country, go to ni.com/citizenship/weee.

**电子信息产品污染控制管理办法 （中国 RoHS）**

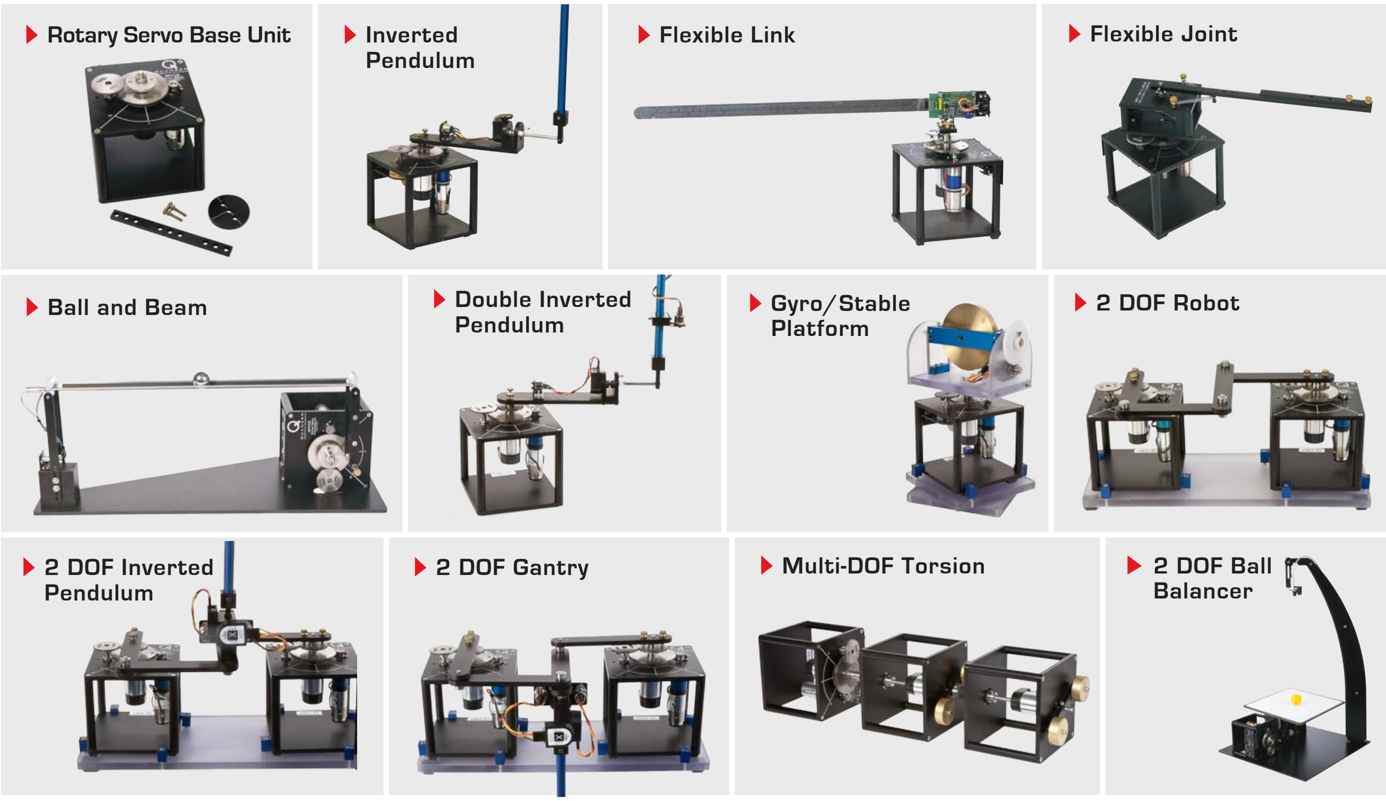
**中国客户** National Instruments 符合中国电子信息产品中限制使用某些有害物质命令 （RoHS）。
关于National Instruments 中国 RoHS合规性信息，请登录 ni.com/environment/rohs_china
(For information about China RoHS compliance, go to ni.com/environment/rohs_china)

**CE Compliance**

This product meets the essential requirements of applicable European Directives as follows:

- 2006/95/EC; Low-Voltage Directive (safety)
- 2004/108/EC; Electromagnetic Compatibility Directive (EMC)

## Over ten rotary experiments for teaching fundamental and advanced controls concepts




Quanser's rotary collection allows you to create experiments of varying complexity – from basic to advanced. Your lab starts with the Rotary Servo Base Unit and is designed to help engineering educators reach a new level of efficiency and effectiveness in teaching controls in virtually every engineering discipline including electrical, computer, mechanical, aerospace, civil, robotics and mechatronics. For more information please contact info@quanser.com.



QUANSER
INNOVATE·EDUCATE