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# STUDENT WORKBOOK

## IP02 Base Unit Experiment for MATLAB®/Simulink® Users

Standardized for ABET* Evaluation Criteria

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# LABORATORY 1

# IP02 MODELING

The objective of this experiment is to find a transfer function that describes the linear motions of the IP02 cart. The dynamic model is derived analytically from classical electromechanical principles.

**Topics Covered**

- Deriving the dynamics equation representing the linear motion servo plant using first-principles.
- Obtaining the transfer function that describes the cart velocity with respect to the motor input voltage from the dynamic equation previously found.
- Tuning the obtained transfer function and validating it with the actual system response.

**Prerequisites**

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

- The required software and hardware outlined in Section 1.4.
- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Basics of QUARC®.
- Laboratory described in the QUARC Intergation Section A in order to be familiar using QUARC® with the IP02.

# 1.1 Background

The linear velocity of the IP02 cart with respect to the input motor voltage can be described by the following first-order transfer function

$$\frac{V_c(s)}{V_m(s)} = \frac{K}{\tau s + 1} \tag{1.1.1}$$

where $V_c$ is the Laplace transform of the cart speed $v_c(t)$, $V_m(s)$ is the Laplace transform of motor input voltage $v_m(t)$, $K$ is the steady-state gain, $\tau$ is the time constant, and $s$ is the Laplace operator.

The IP02 transfer function model is derived analytically in Section 1.1.1.

## 1.1.1 Modeling Using First-Principles

If we apply Newton's second law of motion to the IP02 system, we can derive the relationship between the force applied to the cart by the DC motor and resultant motion of the cart as

$$M\dot{v}_c(t) = F_c(t) - B_c v_c(t) \tag{1.1.2}$$

where $M$ is the mass of the cart, $v_c$ is the linear velocity of the cart, and $B_{eq}$ is the equivalent viscous damping coefficient as seen at the motor pinion. The inertial force due to the motor's armature in rotation is neglected.

The driving force, $F_c$, generated by the DC motor and acting on the cart through the motor pinion can be expressed as

$$F_c = \frac{\eta_g K_g \tau_m}{r_{mp}} \tag{1.1.3}$$

where $\eta_g$ is the planetary gearbox efficiency, $K_g$ is the gear ratio, $\tau_m$ is the torque generated by the motor, and $r_{mp}$ is the motor pinion radius.

To determine $F_c$ as a function of the motor voltage, we will first focus on the electrical components of the system.

The DC motor armature circuit schematic is illustrated in Figure 1.1.1. Recall, as specified in [2], that $R_m$ is the motor resistance, $L_m$ is the inductance, $B_m$ is the motor damping, and $k_m$ is the back-emf constant.

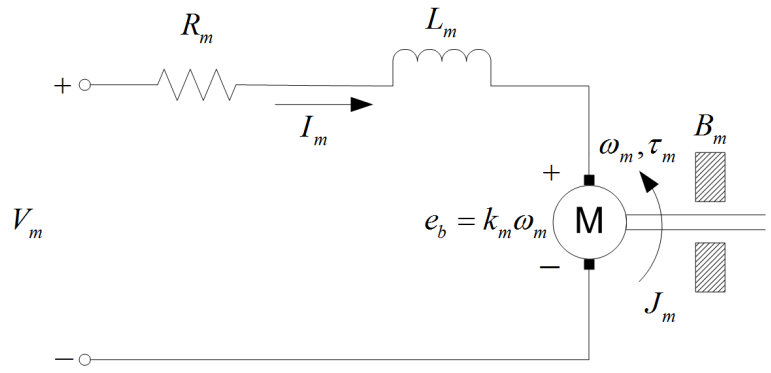



Figure 1.1.1: IP02 DC motor armature circuit

As is illustrated in Figure 1.1.1, the back-emf (electromotive) voltage, $e_b$, depends on the speed of the motor shaft and the back-emf constant of the motor according to

$$e_b(t) = k_m\omega_m(t) = 0$$

Using Kirchoff's Voltage Law, which states that voltages in a closed-loop circuit must be equal to zero, we can write the following equation

$$V_m(t) - R_m I_m(t) - L_m\dot{I}_m(t) - k_m\omega_m(t) = 0$$

Since the motor inductance, $L_m$ is much less than its resistance, it can be ignored. Solving for $I_m(t)$, the motor current can be described as

$$I_m(t) = \frac{V_m(t) - k_m\omega_m(t)}{R_m} \tag{1.1.4}$$

By introducing the motor torque constant, $k_t$, we can relate the motor current to the torque generated by the motor as

$$\tau_m(t) = \eta_m k_t I_m(t) \tag{1.1.5}$$

where $\tau_m$ is the motor torque, and $\eta_m$ is the motor efficiency.

We can now begin to pull together the electrical and mechanical equations into a complete equation of motion for the IP02 system. Substituting Equation 1.1.4 and Equation 1.1.5 into Equation 1.1.3 yields:

$$F_c(t) = \frac{\eta_g K_g \eta_m k_t (V_m(t) - k_m\omega_m(t))}{R_m r_{mp}} \tag{1.1.6}$$

The translation between the angular velocity of the motor shaft and the linear velocity of the cart can be expressed as

$$\omega_m(t) = \frac{K_g v_c(t)}{r_{mp}} \tag{1.1.7}$$

which allows us to define the force applied to the cart in terms of the linear velocity of the cart by substituting Equation 1.1.7 into Equation 1.1.6 as

$$F_c(t) = \frac{\eta_g K_g \eta_m k_t (V_m(t) r_{mp} - k_m K_g v_c(t))}{r_{mp}^2 R_m} \tag{1.1.8}$$

Now that we have the force applied to the cart expressed as a function of the input voltage, we substitute Equation 1.1.8 into the equation of motion Equation 1.1.2

$$M\dot{v_c}(t) + B_c v_c(t) = \frac{\eta_g K_g \eta_m k_t \left(V_m(t) r_{mp} - k_m K g v_c(t)\right)}{r_{mp}^2 R_m}$$

After collecting the terms, the equation becomes

$$M\dot{v_c}(t) + \left(\frac{k_m \eta_g K_g^2 \eta_m k_t}{r_{mp}^2 R_m} + B_c\right) v_c(t) = \frac{\eta_g K_g \eta_m k_t V_m(t)}{r_{mp} R_m}$$

This equation can be re-written as

$$M\dot{v_c}(t) + B_{eq} v_c(t) = A_m V_m(t) \tag{1.1.9}$$

where the equivalent damping term is given by

$$B_{eq} = \frac{\eta_g K_g^2 \eta_m k_t k_m + B_c r_{mp}^2 R_m}{r_{mp}^2 R_m} \tag{1.1.10}$$

and the actuator gain equals

$$A_m = \frac{\eta_g K_g \eta_m k_t}{r_{mp} R_m} \tag{1.1.11}$$

# 1.2 Pre-Lab Questions

Before you begin the lab experiments in Section 1.3, you should study the background material presented in Section 1.1, and work through the questions in this section.

1. In Section 1.1, we obtained Equation 1.1.9 that described the dynamic behavior of the cart speed, $v_c$, as a function of the motor input voltage, $v_m$. Starting from this equation, find the transfer function $\frac{V_c(s)}{V_m(s)}$.

2. Express the steady-state gain, $K$, and the time constant, $\tau$, of the first-order process model in terms of the $M$, $B_m$, and $A_m$ parameters.

3. In the analysis performed in Section 1.1, the inertial force due to the rotating motor armature was neglected. If the inertial force of the motor armature as seen at the cart is included in the equation of motion, by applying Newton's second law of motion and D'Alembert's principle we can recreate Equation 1.1.2 as

$$M\dot{v}_c(t) + F_{aj}(t) = F_c(t) - B_c v_c(t) \tag{1.2.1}$$

   The armature inertial force due to the motor rotation acting on the cart can be expressed as a function of the armature inertial torque using

$$F_{aj} = \frac{\eta_g K_g \tau_{aj}}{r_{mp}} \tag{1.2.2}$$

   By applying Newton's Second Law of motion, we can express the armature inertial torque as

$$J_m \dot{\omega}_m(t) = \tau_{aj}(t) \tag{1.2.3}$$

   Generate the equation of motion for the more accurate model.

4. How will the revised model you found in Question 3 affect the steady-state gain, $K$, and the time constant, $\tau$? Revise the model parameters if necessary.

# 1.3 In-Lab Exercises

The main goal of this laboratory is to find a transfer function (model) that describes the linear motion of the IP02 cart as a function of the input voltage.

In this laboratory, you will conduct an experiment to fine tune the parameters of the transfer function you calculated in Section 1.2 to validate them.

**Experiment Setup**

The q_ip02_mdl Simulink diagram shown in Figure 1.3.1 is used to perform the modeling exercises in this laboratory. The *IP02 Speed* subsystem contains QUARC blocks that interface with the DC motor and sensors of the IP02 system, as discussed in the QUARC Integration Lab Section A. The *IP02 Plant Model* subsystem uses a *Transfer Fcn* block from the Simulink library to simulate the IP02 system. Thus both the measured and simulated cart speed can be monitored simultaneously given the set open-loop input voltage.

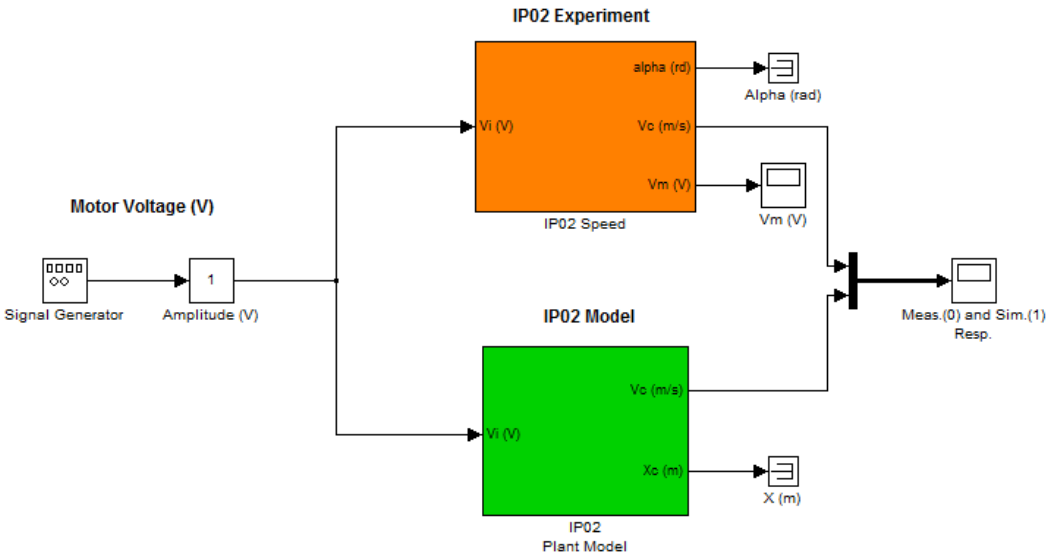



Figure 1.3.1: q_ip02_mdl Simulink diagram used to model IP02

**Note:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your IP02 setup. If they have not been configured already, then go to Section 1.4.2 to configure the lab files before you begin.

## 1.3.1 Model Validation Experiment

In this experiment we will adjust the parameters you found in Section 1.2 to tune the transfer function. Our goal is to match the simulated response as closely as possible to the response of the actual system.

To create a step input:

1. Double-click on the *Signal Generator* block and ensure the following parameters are set:
   - Wave form: square
   - Amplitude: 1.0
   - Frequency: 1
   - Units: Hertz

2. Set the *Amplitude (V)* slider to 1.0 V.
3. Open the speed scope, *Meas.(0) and Sim.(1) Resp.*, and the motor input voltage scope, *Vm (V)*.
4. Click on QUARC | Build to compile the Simulink diagram.
5. Select QUARC | Start to run the controller. The IP02 cart should begin moving back and forth along the track, and the scopes should be as shown in figures 1.3.2 and 1.3.3. Recall that the yellow trace is the measured cart speed and the purple trace is the simulated trace. By default, the steady-state gain and the time constant of the transfer function used in simulation are set to: $K = 0.1$ rad/s/V and $\tau = 0.01$ s. These model parameters do not accurately represent the system.

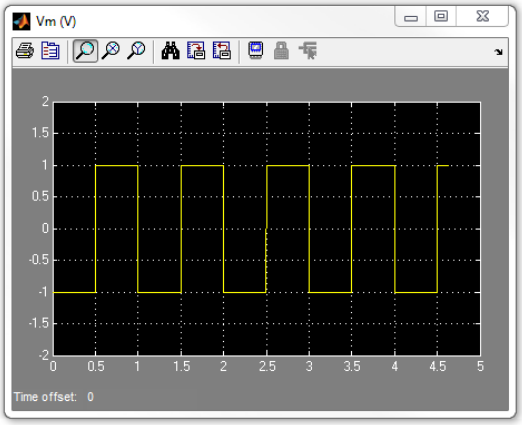



Figure 1.3.2: Input square voltage.

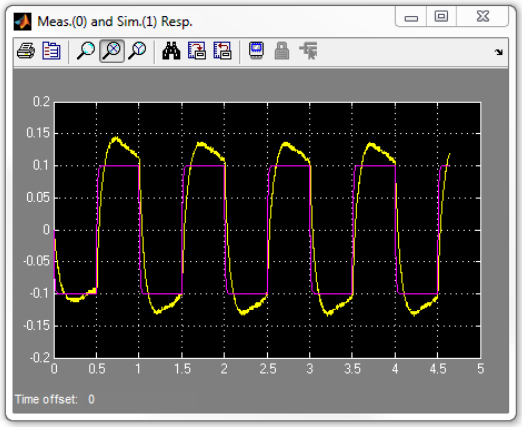



Figure 1.3.3: Speed step response. Simulation done with default model parameters: $K = 0.1$ and $\tau = 0.01$.

6. Enter the command $K = 0.125$ in the MATLAB Command Window.
7. Update the parameters used by the Transfer Function block in the simulation by selecting the Edit | Update Diagram item in the q_ip02_mdl Simulink diagram and observe how the simulation changes.
8. Enter the command $tau = 0.02$ in the MATLAB Command Window.
9. Update the simulation again by selecting the Edit | Update Diagram and observe how the simulation changes.
10. Vary the gain and time constant model parameters. How do the gain and the time constant affect the system response?
11. Calculate the model parameters $B_{eq}$, $A_m$ and the equivalent innertia term, $J_{eq}$, where $J_{eq}$ is the acceleration coefficient from Question 3 in Section 1.2 using the appropriate workspace variables. Then use Matlab® to calculate the nominal values, $K$ and $\tau$, that were defined in Section Section 1.2.
12. Enter the nominal values, $K$ and $\tau$, that were found in Question 11 in the MATLAB Command Window. Update the parameters and examine how well the simulated response matches the measured one.
13. Create a MATLAB figure that compares the simulated and experimental response, and provide two reasons why the nominal model does not represent the IP02 with better accuracy. When the model is stopped, the *Meas.(0) and Sim.(1) Resp.* scope saves the last five seconds of response data to the MATLAB workspace in the *data_x_comp* parameter. It has the following structure: *data_x_comp(:,1)* is the time vector, *data_x_comp(:,2)* is the measured position, and *data_x_comp(:,3)* is the simulated position.
14. Try varying the model parameters until the simulated trace matches the measured response better. Record your tuned values.
15. Create a MATLAB figure that shows the measured and simulated response of the system using the nominal and tuned parameters. Recall that the position data is automatically saved each time the model is run in the MATLAB workspace under the *data_x_comp* variable.

# 1.4 System Requirements

Before you begin this laboratory make sure:

- QUARC® is installed on your PC, as described in the QUARC Installation Guide [3].
- You have a QUARC compatible data-aquisition (DAQ) card installed in your PC. For a listing of compliant DAQ cards, see the QUARC User Manual [1].
- IP02 and amplifier are connected to your DAQ board as described the IP02 User Manual [2].

## 1.4.1 Overview of Files

| File Name | Description |
|---|---|
| IP02 Modeling Workbook (Student).pdf | This laboratory guide contains pre-lab and in-lab exercises demonstrating how to model the Quanser IP02 linear plant. The in-lab exercises are explained using the QUARC software. |
| setup_ip02_modeling.m | The main Matlab® script that sets the IP02 model 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,* and *eta_m,* the sensor calibration constant *K_ENC* and the amplifier limits *VMAX_AMP* and *IMAX_AMP*. |
| q_ip02_mdl.mdl | Simulink® file that implements the open-loop IP02 model using QUARC. |

Table 1.4.1: Files supplied with the IP02 Modeling Laboratory.

## 1.4.2 Configuring the IP02 and the Lab Files

Before beginning the lab exercises the IP02 device, the q_ip02_mdl Simulink diagram, and the setup_ip02_modeling.m script must be configured.

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

1. Set up the IP02 without the additional weight as described in the IP02 User Manual [2].
2. Load the Matlab® software.
3. Browse through the Current Directory window in Matlab® and find the folder that contains the IP02 modeling files, e.g. q_ip02_mdl.mdl.
4. Double-click on the q_ip02_mdl.mdl file to open the Simulink diagram shown in Figure 1.3.1.
5. **Configure DAQ:** Double-click on the HIL Initialize block in the Simulink diagram and ensure it is configured for the DAQ device that is installed in your system. For instance, the block shown in Figure 1.3.1 is setup for the Quanser Q2-USB hardware-in-the-loop board. See the QUARC Installation Guide [3] for more information on configuring the HIL Initialize block.
6. Go to the *Current Directory* window and double-click on the setup_ip02_modeling.m file to open the setup script for the q_ip02_mdl Simulink model.

7. **Configure setup script:** The beginning of the setup script is shown below. Ensure the script is setup to match the configuration of your actual IP02 device. For example, the script given below is setup for an IP02 plant without the additional weight and it is actuated using the Quanser VoltPAQ device with a gain of 1. See the IP02 User Manual [2] for more information on IP02 plant options and corresponding accessories.
   Finally, make sure MODELING_TYPE is set to 'MANUAL'.

```
% ############### IP02 CONFIGURATION ###############
% Type of Cart Load: set to 'NO_LOAD', 'WEIGHT'
IP02_LOAD_TYPE = 'NO_LOAD';
% IP02_LOAD_TYPE = 'WEIGHT';
% Turn on or off the safety watchdog on the cart position: set it to 1 , or 0
X_LIM_ENABLE = 1;       % safety watchdog turned ON
%X_LIM_ENABLE = 0;      % safety watchdog turned OFF
% Safety Limits on the cart displacement (m)
X_MAX = 0.3;            % cart displacement maximum safety position
X_MIN = - X_MAX;        % cart displacement minimum safety position
% Amplifier Gain: set VoltPAQ amplifier gain to 1
K_AMP = 1;
% Power Amplifier Type: set to 'VoltPAQ'
AMP_TYPE = 'VoltPAQ';
% Digital-to-Analog Maximum Voltage (V); for Q2-USB cards set to 10
VMAX_DAC = 10;
% ##############################

% ############### LAB CONFIGURATION ###############
% Type of Controller: set it to 'AUTO', 'MANUAL'
% MODELING_TYPE = 'AUTO';
MODELING_TYPE = 'MANUAL';
% ##############################
```

8. Run the script by selecting the Debug | Run item from the menu bar or clicking on the *Run* button in the tool bar.

# LABORATORY 2

# IP02 POSITION CONTROL

The objective of this laboratory is to develop a feedback system to control the position of the IP02 cart. Using a proportional-velocity (PV) control scheme, a controller is designed to meet a set of specifications.

**Topics Covered**

- Design of a proportional-velocity (PV) controller for position control of the linear servo within particular requirements.
- Simulation of the PV controller using a developed plant model to ensure the specifications are met.
- Implementation of the controller on the Quanser IP02 to evaluate performance.

**Prerequisites**

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

- The required software and hardware outlined in Section 2.4.
- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Basics of QUARC®.
- Laboratory described in the QUARC Intergation Section A in order to be familiar using QUARC® with the IP02.

# 2.1 Background

## 2.1.1 Desired Position Control Response

The block diagram shown in Figure 2.1.1 is a general unity feedback system with compensator (controller), $C(s)$, and a transfer function representing the plant model, $P(s)$. The measured output, $Y(s)$, tracks the reference signal, $R(s)$, within a particular set of design specifications.

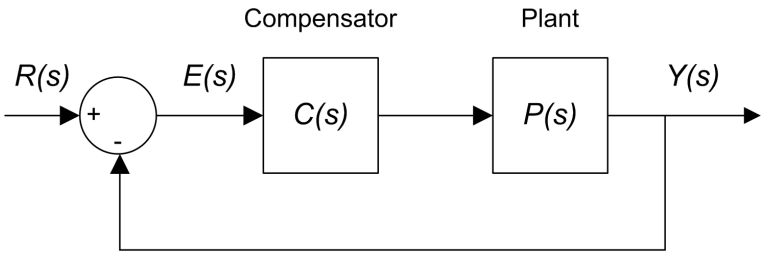



Figure 2.1.1: Unity feedback system

The output of this system can be written as:

$$Y(s) = C(s)P(s)(R(s) - Y(s))$$

By solving for $Y(s)$, we can find the closed-loop transfer function:

$$P(s) = \frac{Y(s)}{R(s)} = \frac{C(s)P(s)}{1 + C(s)P(s)} \tag{2.1.1}$$

Recall in *Linear Servo Modeling* [5], the IP02 voltage-to-speed transfer function was derived. To find the voltage-to-position transfer function, we can introduce an integrator ($1/s$) in series with the speed transfer function (effectively integrating the speed to get position). The resulting voltage-to-position transfer function becomes:

$$P(s) = \frac{K}{s(\tau s + 1)} \tag{2.1.2}$$

As you can see from Equation 2.1.2, the plant is a second order system. In fact, when a second order system is placed in series with a proportional compensator in the feedback loop as shown in Figure 2.1.1, the resulting closed-loop transfer function can be expressed as:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{2.1.3}$$

where $\omega_n$ is the natural frequency and $\zeta$ is the damping ratio. This is called the *standard second-order* transfer function. Its response properties depend on the values of $\omega_n$ and $\zeta$.

## 2.1.2 Peak Time and Overshoot

Consider a second-order system as shown in Equation 2.1.3, subjected to a step input given by

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

with a step amplitude of 1.5. The system response to this input is shown in Figure 2.1.2, where the red trace is the response (output), $y(t)$, and the blue trace is the step input, $r(t)$. The maximum value of the response is denoted by the variable $y_{max}$ and it occurs at time $t_{max}$. For a response similar to Figure 2.1.2, the *percent overshoot* is found using

$$PO = \frac{100(y_{max} - R_0)}{R_0}.$$

From the initial step time, $t_0$, the time it takes for the response to reach its maximum value is

$$t_p = t_{max} - t_0.$$

This is called the *peak time* of the system.

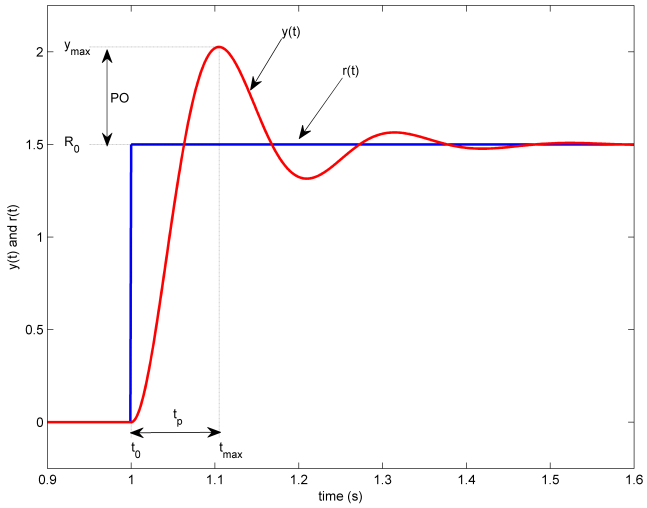



Figure 2.1.2: Standard second-order step response

In a second-order system, the amount of overshoot depends solely on the damping ratio parameter and it can be calculated using the equation

$$PO = 100e^{\left(\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}\right)}. \tag{2.1.4}$$

The peak time depends on both the damping ratio and the natural frequency of the system, and can be derived as:

$$t_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \tag{2.1.5}$$

Generally speaking, the damping ratio affects the shape of the response while the natural frequency affects the speed of the response.

## 2.1.3 Steady-State Error

Steady-state error is illustrated in the ramp response given in Figure 2.1.3 and is denoted by the variable $e_{ss}$. It is the difference between the reference input and output signals after the system response has settled. Thus, for a time $t$ when the system is in steady-state, the steady-state error equals:

$$e_{ss} = r_{ss}(t) - y_{ss}(t) \tag{2.1.6}$$

where $r_{ss}(t)$ is the value of the steady-state input and $y_{ss}(t)$ is the steady-state value of the output.

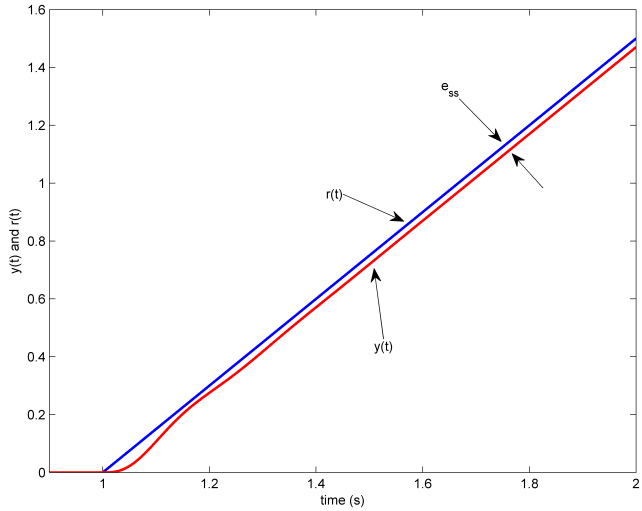



Figure 2.1.3: Steady-state error in ramp response

We can find the error transfer function $E(s)$ in Figure 2.1.1 in terms of the reference $R(s)$, the plant $P(s)$, and the compensator $C(s)$. The Laplace transform of the error is

$$E(s) = R(s) - Y(s) \tag{2.1.7}$$

Solving for $Y(s)$ from Equation 2.1.7 and substituting it into Equation 2.1.1 yields

$$E(s) = \frac{R(s)}{1 + C(s)P(s)} \tag{2.1.8}$$

## 2.1.4 IP02 Position Control Specifications

The desired time-domain specifications for controlling the position of the IP02 position are:

$$t_p = 0.15s$$
$$PO = 10\%$$

and

$$e_{ss} = 0$$

Therefore, when tracking the position reference, the transient response should have a peak time less than or equal to 0.15 seconds, an overshoot of less than or equal to 10%, and a steady-state response with no error.

## 2.1.5 PID Control

The control action of a proportional, integral, and derivative (PID) controller can be expressed mathematically as follows

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \dot{e}(t) \tag{2.1.9}$$

where $k_p$ is the proportional gain, $k_i$ is the integral gain, $k_d$ is the derivative gain, and $e(t)$ is the feedback error where $e(t) = r(t) - y(t)$. The PID controller can also be described by the transfer function

$$C(s) = k_p + \frac{k_i}{s} + k_d s \tag{2.1.10}$$

The corresponding block diagram is given in Figure 2.1.4.

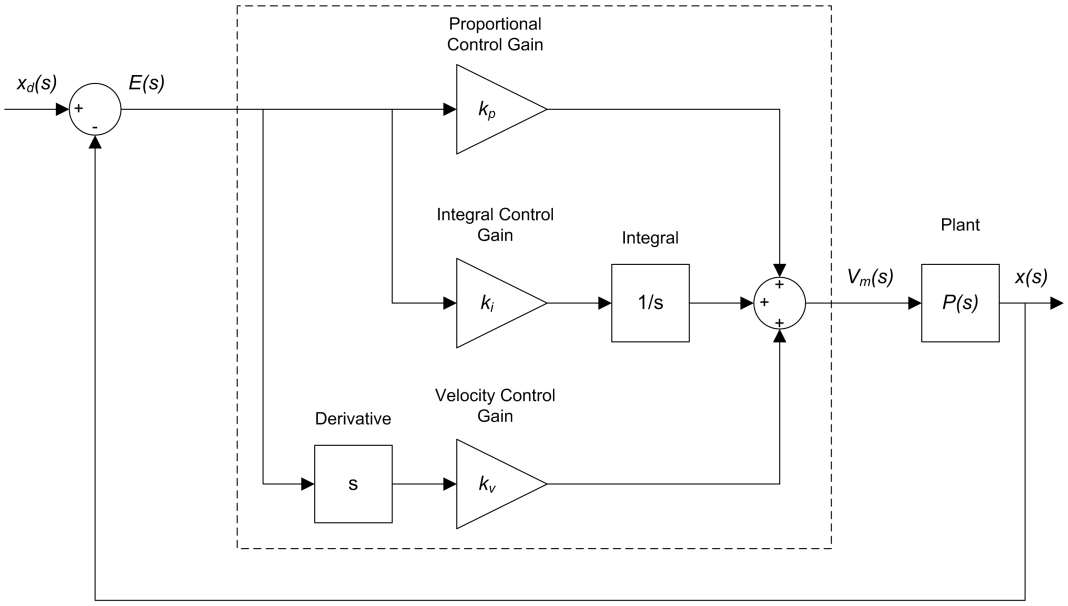



Figure 2.1.4: Block diagram of PID control

The proportional term is based on the the present error, the integral term depends on past errors, and the derivative term is a prediction of future errors. Advanced model-based controllers differ from the PID controller by using a model of the process for prediction.

The PID controller described by Equation 2.1.9 is the ideal PID controller. Attempts to implement these formulas directly may not yield good controllers. For example, most measurement signals are subject to noise, which can result in very large fluctuations when differentiated.

### 2.1.5.1 PV Control

In order to control the position of the linear servo cart, a variation of the classic PD control will be used: proportional-velocity (PV) control, illustrated in Figure 2.1.5. Unlike the standard PD control scheme, the negative velocity is

fed back (as opposed to the velocity of the error) and a high-pass filter, $H(s)$ is used instead of a direct derivative. Filtering the differentiated signal reduces the noise in the negative velocity term.

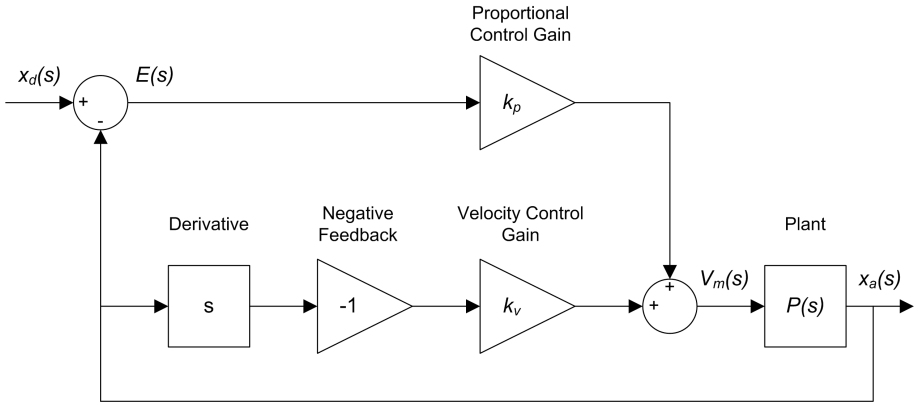



Figure 2.1.5: Block diagram of PV control

The PV control strategy has the following structure

$$u = k_p(r(t) - y(r)) - k_v\dot{y}(t)$$

where $k_p$ is the proportional gain, $k_d$ is the derivative gain, $r = x_d(t)$ is the setpoint cart position, $y = x_a(t)$ is the measured cart position, and $u = V_m(t)$ is the control input or IP02 motor input voltage.

# 2.2 Pre-Lab Questions

Before you begin the lab experiments in Section 2.3, you should study the background material presented in Section 2.1, and work through the questions in this section.

1. Find the closed-loop transfer function $Y(s)/R(s) = X_a(s)/X_d(s)$ for the closed-loop PV position control of the IP02. Assume all initial conditions are zero, i.e., $x_a(0^-) = 0$ and $\dot{x}_a(0^-) = 0$.
2. Using IP02 closed-loop transfer function that was derived in Step 1, find the control gains $k_p$, and $k_v$ in terms of $\omega_n$ and $\zeta$. **Hint:** Remember the standard second order system Equation 2.1.3.
3. Calculate the minimum damping ratio and natural frequency required to meet the design specifications listed in Section 2.1.4.
4. Based on the nominal IP02 model parameters, $K$ = 0.1433 m/(V-s) and $\tau$ = 0.0584 s, found in *Linear Servo Modeling* [5], calculate the control gains needed to satisfy the time-domain response requirements listed in Section 2.1.4.
5. Find the steady-state error of the system, $e_{ss}$, for the step input $R(s) = \frac{R_0}{s}$, where $R_0$ is the desired cart position. Use the PV control equation from Step 1, and the error transfer function Equation 2.1.7. **HINT:** Use the Final-Value Theorem.

# 2.3 In-Lab Exercises

The goal of this laboratory is to explore position control of the IP02 cart using a PV controller. You will conduct an experiment to fine tune the parameters of the PV controller you calculated in Section 2.2 to validate them.

## 2.3.1 Simulation

First, you will simulate the closed-loop response of the IP02 with a PV controller to a step input. Our goals are to confirm that the desired response specifications in an ideal situation are satisfied, and to verify that the motor is not saturated.

**Experiment Setup**

The s_ip02_position Simulink diagram shown in Figure 2.3.1 is used to simulate the closed-loop position control response with the PV controller. The *IP02 Model* subsystem uses a *Transfer Fcn* block from the Simulink library to simulate the IP02 system. The *PV Control* subsystem contains the PV controller detailed in Section 2.1.5.1.

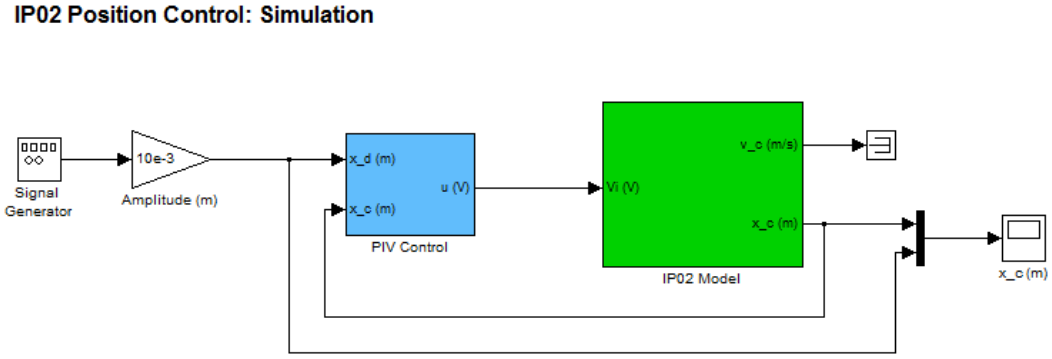



Figure 2.3.1: Simulink diagram used to simulate the IP02 closed-loop position response

**Note:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your IP02 setup. If they have not been configured already, then go to Section 2.4.2 to configure the lab files before you begin.

**Closed-loop Response with the PV Controller**

1. Run the *setup_ip02_position* script.
2. To generate a step reference, ensure the *Signal Generator* is set to the following:
   - Signal type = *square*
   - Amplitude = 1
   - Frequency = 0.66 Hz
3. In the Simulink diagram, set the *Amplitude (m)* gain block to $0.01$ to generate a step with an amplitude of 10 millimeters (i.e., square wave goes between $\pm 0.01$ m which results in a step amplitude of $0.02$ m).
4. Inside the *PV Control* subsystem, set the *Manual Switch* to the upward position so the *Derivative block* is used.
5. Open the cart position scope, *x_c (m)*, and the motor input voltage scope, *Vm (V)*.
6. Start the simulation. By default, the simulation runs for 5 seconds. The scopes should be displaying responses similar to figures 2.3.2 and 2.3.3. Note that in the *x_c (m)* scope, the yellow trace is the setpoint position while the purple trace is the simulated position (generated by the *IP02 Model* block). This simulation is called the *Ideal PV* response as it uses the PV compensator with the derivative block.

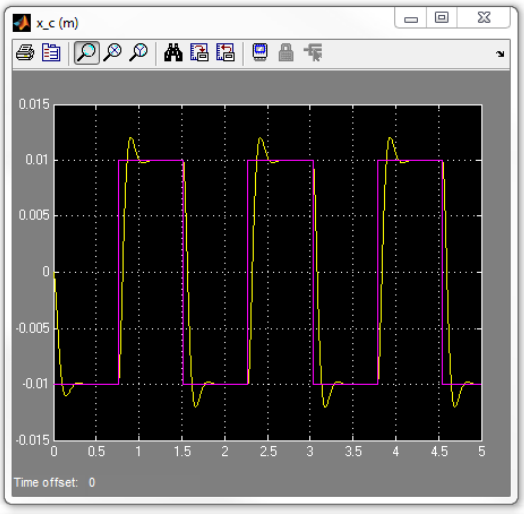



Figure 2.3.2: Ideal PV position response.

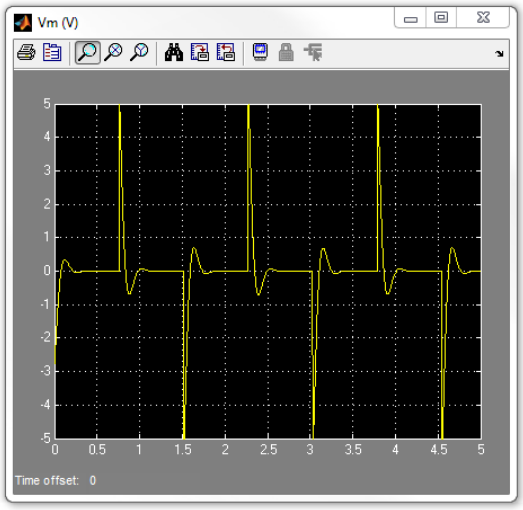



Figure 2.3.3: Ideal PV motor input voltage.

7. Change the proportional gain, $k_p$, and examine its effect on the response. In particular, what happens to the overshoot and settling time as $k_p$ is increased?
8. Change the velocity gain, $k_v$, and examine its effect on the response. In particular, what happens to the settling time and overshoot?
9. Enter the proportional and velocity control gains found in Pre-Lab question 2 in Matlab® as *kp* and *kv*.
10. Generate a MATLAB figure showing the *Ideal PV* position response and the ideal input voltage. After each simulation run, each scope automatically saves their response to a variable in the MATLAB workspace. That is, the *x_c (m)* scope saves its response to the variable called data_pos and the *Vm (V)* scope saves its data to the *data_vm* variable. The *data_pos* variable has the following structure: *data_pos(:,1)* is the time vector, *data_pos(:,2)* is the simulated angle, and *data_pos(:,3)* is the setpoint. For the *data_vm* variable, *data_vm(:,1)* is the time and *data_vm(:,2)* is the simulated input voltage.
11. Measure the steady-state error, the percent overshoot and the peak time of the simulated response. Does the response satisfy the specifications given in Section Section 2.1.4? **Hint:** Use the MATLAB *ginput* command to take measurements off the figure.

## 2.3.2 Implementing PV Controller

In this experiment, you will control the position of the IP02 cart using the PV controller. Measurements will then be taken to ensure that the specifications are satisfied.

**Experiment Setup**

The q_ip02_position Simulink diagram shown in Figure 2.3.4 is used to implement the position control experiments. The *IP02 Position* subsystem contains QUARC blocks that interface with the DC motor and sensors of the IP02 system, as discussed in the QUARC Integration Lab Section A. The *PV Control* subsystem implements the PV controller detailed in Section 2.1.5.1, except a high-pass filter is used to obtain the velocity signal (as opposed to taking the direct derivative).

**Note:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your IP02 setup. If they have not been configured already, then go to Section 2.4.2 to configure the lab files before you begin.

1. Run the *setup_ip02_position* script.

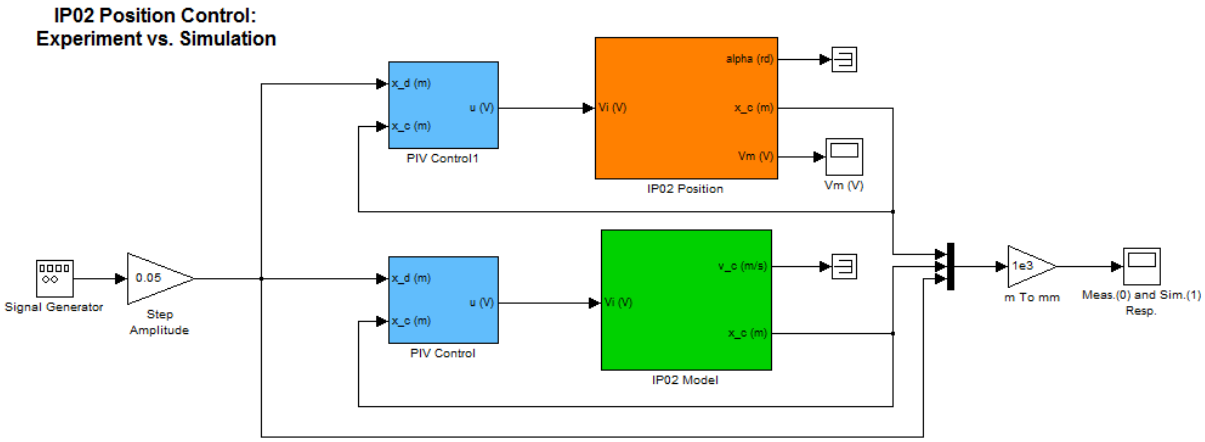



Figure 2.3.4: Simulink diagram used with QUARC to run the PV controller on the IP02

2. Enter the proportional and velocity control gains found in Pre-Lab question 2.
3. Set Signal Type in the *Signal Generator* to *square* to generate a step reference.
4. Set the *Amplitude (m)* gain block to $0.01$ to generate a step with an amplitude of 10 millimeters.
5. Open the cart position scope, *Meas.(0) and Sim.(1) Resp.*, and the motor input voltage scope, *Vm (V)*.
6. Click on QUARC | Build to compile the Simulink diagram.
7. Select QUARC | Start to begin running the controller. The scopes should display responses similar to figures 2.3.5 and 2.3.6 Note that in the *x_c (m)* scope, the yellow trace is the measured position, the purple trace is the simulated position, and the cyan trace is the setpoint.

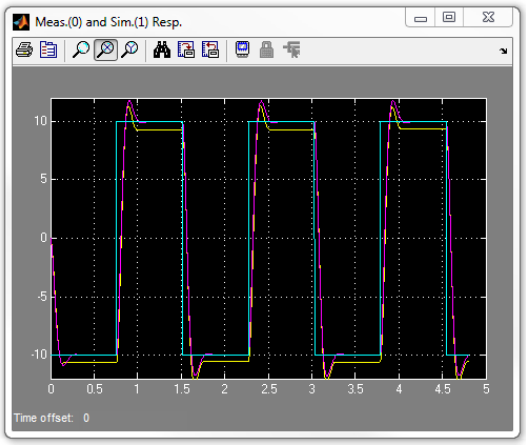



Figure 2.3.5: Measured PV step response.

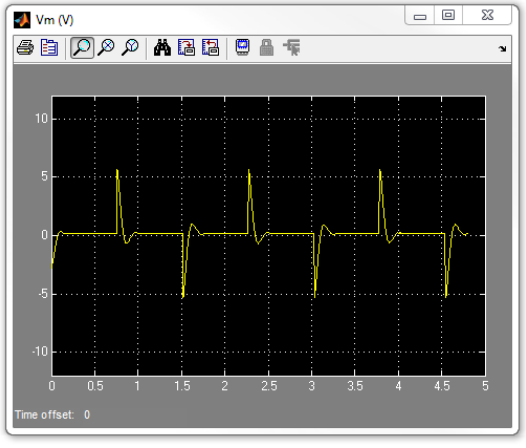



Figure 2.3.6: PV control input voltage.

8. When a suitable response is obtained, click on the Stop button in the Simulink diagram toolbar (or select QUARC | Stop from the menu) to stop running the code.
9. Generate a MATLAB figure showing the measured PV position response and its input voltage. As in the *s_ip02_position* Simulink diagram, when the controller is stopped each scope automatically saves their response to a variable in the MATLAB workspace. Thus, the *x_c (m)* scope saves its response to the *data_xc* variable and the *Vm (V)* scope saves its data to the *data_vm* variable.
10. Measure the steady-state error, the percent overshoot, and the peak time of the IP02. Does the response satisfy the specifications given in Section 2.1.4?

11. Why do the experimental results not match the simulated model response?
12. How could you alter the controller to compensate for the steady-state error?
13. Click the Stop button on the Simulink diagram toolbar (or select QUARC | Stop from the menu) to stop the experiment.
14. Turn off the power to the amplifier if no more experiments will be performed on the IP02 in this session.

# 2.4 System Requirements

Before you begin this laboratory make sure:

- QUARC® is installed on your PC, as described in Reference [3].
- You have a QUARC compatible data-aquisition (DAQ) card installed in your PC. For a listing of compliant DAQ cards, see Reference [1].
- IP02 and amplifier are connected to your DAQ board as described Reference [2].

## 2.4.1 Overview of Files

| File Name | Description |
|---|---|
| IP02 Position Control Workbook (Student).pdf | This laboratory guide contains pre-lab and in-lab exercises demonstrating position control of the Quanser IP02 linear plant. The in-lab exercises are explained using the QUARC software. |
| setup_ip02_position.m | The main Matlab® script that sets the IP02 position control parameters. **Run this file only to setup the laboratory.** |
| setup_ip02_configuration.m | Returns the configuration-based IP02 model specifications *Rm, Jm, Kt, Eff_m, Km, Kg, Eff_g, M, r_mp,* and *Beq* |
| d_model_param.m | Determines the model parameters *K*, and *tau*. |
| s_ip02_position.mdl | Simulink file that simulates the closed-loop IP02 position control step response. |
| q_ip02_position.mdl | Simulink file that implements the closed-loop IP02 position controller using QUARC. |

Table 2.4.1: Files supplied with the IP02 Position Control Laboratory.

## 2.4.2 Configuring the IP02 and the Lab Files

Before beginning the lab exercises the IP02 device, the q_ip02_position Simulink diagram and the setup_ip02_position.m script must be configured.

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

1. Set up the IP02 without the additional weight as described in [2].
2. Load the Matlab® software.
3. Browse through the Current Directory window in Matlab® and find the folder that contains the IP02 modeling files, e.g. q_ip02_position.mdl.
4. Double-click on the q_ip02_position.mdl file to open the Simulink diagram shown in Figure Figure 2.3.4.
5. **Configure DAQ:** Double-click on the HIL Initialize block in the Simulink diagram and ensure it is configured for the DAQ device that is installed in your system. For instance, the block shown in Figure 2.3.4 is setup for the Quanser Q2-USB hardware-in-the-loop board. See the QUARC Installation Guide [3] for more information on configuring the HIL Initialize block.

6. Go to the *Current Directory* window and double-click on the setup_ip02_position.m file to open the setup script for the q_ip02_position Simulink model.

7. **Configure setup script:** The beginning of the setup script is shown below. Ensure the script is setup to match the configuration of your actual IP02 device. For example, the script given below is setup for an IP02 plant without the additional weight and it is actuated using the Quanser VoltPAQ device with a gain of 1. See the IP02 User Manual [2] for more information on IP02 plant options and corresponding accessories.
   Finally, make sure MODELING_TYPE is set to 'MANUAL'.

```
% ############### IP02 CONFIGURATION ###############
% if IP02: Type of Cart Load: set to 'NO_LOAD', 'WEIGHT'
IP02_LOAD_TYPE = 'NO_LOAD';
% IP02_LOAD_TYPE = 'WEIGHT';
% Turn on or off the safety watchdog on the cart position: set it to 1 , or 0
X_LIM_ENABLE = 1;       % safety watchdog turned ON
%X_LIM_ENABLE = 0;      % safety watchdog turned OFF
% Safety Limits on the cart displacement (m)
X_MAX = 0.3;            % cart displacement maximum safety position
X_MIN = - X_MAX;        % cart displacement minimum safety position
% Amplifier Gain: set VoltPAQ amplifier gain to 1
K_AMP = 1;
% Power Amplifier Type: set to 'VoltPAQ' or 'Q3'
AMP_TYPE = 'VoltPAQ';
% Digital-to-Analog Maximum Voltage (V); for Q2-USB cards set to 10
VMAX_DAC = 10;

% ############### USER-DEFINED CONTROLLER DESIGN ###############
% Type of Controller: set it to 'PV', 'MANUAL'
%CONTROLLER_TYPE = 'AUTO_PV';     % PV controller design: automatic mode
CONTROLLER_TYPE = 'MANUAL';    % controller design: manual mode
% PV Controller Design Specifications
PO = 10;         % spec #1: maximum of 10% overshoot
tp = 0.15;     % spec #2: 150 ms time of first peak
```

8. Run the script by selecting the Debug | Run item from the menu bar or clicking on the *Run* button in the tool bar.

# LABORATORY 3

# IP02 SPEED CONTROL

The objective of this laboratory is to develop a feedback system to control the speed of the IP02 cart. A lead compensator is designed to regulate the speed of the linear cart accoding to a set of specifications.

**Topics Covered**

- Design of a lead compensator for speed control of the linear servo within particular requirements.
- Simulation of the lead compensator using the plant model to ensure the specifications are met without saturating the actuator.
- Implementation of the controller on the Quanser IP02 to evaluate performance.

**Prerequisites**

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

- The required software and hardware outlined in Section 3.4.
- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Basics of QUARC®.
- Laboratory described in the QUARC Intergation Section A in order to be familiar using QUARC® with the IP02.

# 3.1 Background

## 3.1.1 Desired Speed Control Response

The following frequency-domain design requirements are are to be met when designing the lead compensator to reduce steady-state errror, and increase the bandwidth and phase margin of the system to improve the transiant response:

$$\omega_c = 80 \text{ rad/s}$$

$$\phi_m = 85 \text{ deg}$$

**The phase margin** mainly affects the shape of the response. Having a higher phase margin implies that the system is more stable and the corresponding time response will have less overshoot.

**The crossover frequency** is the frequency where the gain of the Bode plot is 1 (or 0 dB). This parameter mainly affects the speed of the response, thus having a larger $\omega_c$ decreases the peak time.

These frequency-domain specifications should result in a system that fufills the following time-domain specifications:

$$t_p \leq 0.05 \text{ s}$$

$$PO \leq 5 \text{ \%}$$

$$e_{ss} = 0 \text{ m/s}$$

### 3.1.1.1 Steady State Error

Consider the speed control system with unity feedback shown in Figure 3.1.1. Let the compensator be $C(s) = 1$.

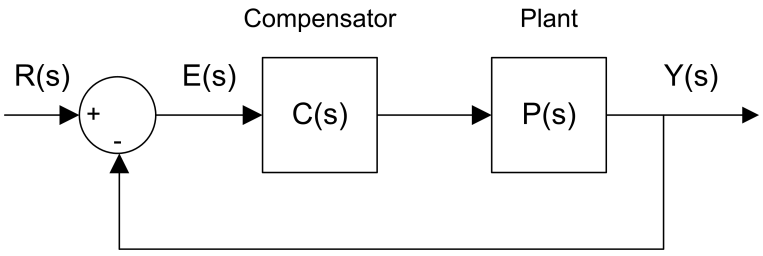



Figure 3.1.1: Unity feedback loop.

We can find the steady-state error using the final value theorem:

$$e_{ss} = \lim_{s \to 0} s\,E(s)$$

where

$$E(s) = \frac{R(s)}{1 + C(s)\,P(s)} \tag{3.1.1}$$

$P(s)$ is the plant transfer function that was determined in the *IP02 Modeling Laboratory* as

$$P(s) = \frac{K}{\tau s + 1} \tag{3.1.2}$$

where $K$ is the steady-state gain and $\tau$ is the time constant.

Substituting $R(s) = \frac{R_0}{s}$ and $C(s) = 1$ gives:

$$E(s) = \frac{R_0}{s\left(1 + \frac{K}{\tau s + 1}\right)}$$

Applying the final-value theorem to the system gives

$$e_{ss} = R_0 \left(\lim_{s \to 0} \frac{\tau s + 1}{\tau s + 1 + K}\right)$$

When evaluated, the resulting steady-state error due to a step response is

$$e_{ss} = \frac{R_0}{1 + K} \tag{3.1.3}$$

## 3.1.2 Lead Control Design

In order to control the speed of the IP02 cart within the specifications outlined in Section 3.1.1, a lead compensator with an integrator, as shown in Figure 3.1.2, will be designed.

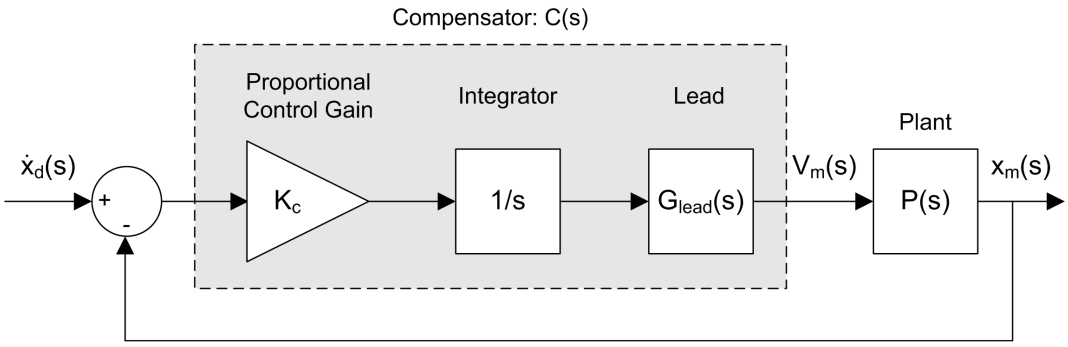



Figure 3.1.2: Closed-loop SRV02 speed control with lead compensator.

To obtain zero steady-state error, an integrator is placed in series with the plant. This system is denoted by the transfer function

$$P_i(s) = \frac{P(s)}{s} \tag{3.1.4}$$

The phase margin and crossover frequency specifications listed in Section 3.1.1 can be satisfied using a proportional gain, $K_c$, and the lead transfer function

$$G_{lead}(s) = \frac{1 + aTs}{1 + Ts} \tag{3.1.5}$$

The $a$ and $T$ parameters change the location of the pole and zero of the lead compensator, which changes the gain and phase margins of the system. The design process involves examining the stability margins of the open-loop transfer function $G(s) = C(s)P(s)$, where the compensator is given by

$$C(s) = \frac{K_c(1 + a\,T\,s)}{s(1 + T\,s)} \tag{3.1.6}$$

#### 3.1.2.1 Finding the Lead Compensator Parameters

The Lead compensator is an approximation of a proportional-derivative (PD) controller. A PD controller can be used to add damping to reduce the overshoot in the transient portion of a step response, and effectively make the system more stable. In other words, it increases the phase margin. In this particular case, the lead compensator is designed for the following system

$$H(s) = \frac{K_c P(s)}{s} \tag{3.1.7}$$

The proportional gain $K_c$ is designed to attain a certain crossover frequency. Increasing the gain crossover frequency essentially increases the bandwidth of the system which decreases the peak-time in the transient response (makes the response faster). However, if $K_c > 1$ the system less is stable since the phase margin of the $H(s)$ system is therefore lower than the phase margin of the $P_i(s)$ system and this translates to having a large overshoot in the response. The lead compensator is used to dampen the overshoot and increase the overall stability of the system, effectively increasing its phase margin.

The frequency response of the lead compensator given in Equation 3.1.5 is

$$G_{lead}\,(\omega\,j) = \frac{1 + a\,T\,\omega j}{1 + T\,\omega\,j}$$

and its corresponding magnitude and phase equations are

$$|G_{lead}(\omega\,j)| = \sqrt{\frac{T^2\,\omega^2\,a^2 + 1}{1 + T^2\,\omega^2}}$$

and

$$\phi_G = \text{arctan}(a\,T\omega) - \text{arctan}(T\,\omega)$$

The Bode plot of the lead compensator is shown in Figure 3.1.3.

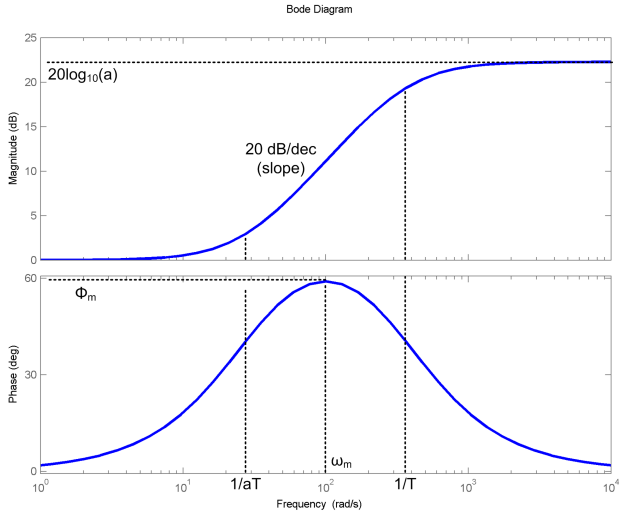



Figure 3.1.3: Bode of lead compensator.

### 3.1.2.2 Lead Compensator Design

In this section, we will design a lead compensator that will satisfy the frequency-based specifications given in Section 3.1.1.

1. **Create a Bode diagram of the open-loop uncompensated system, $P_i(s)$:** To generate the Bode plot of $P_i(s)$, enter the following commands in Matlab®.

   **Note:** If your system has not been set up yet, then you need to first run the the *setup_ip02_speed.m* script, as outlined in Section 3.4.2. This script will create the model parameters *K* and *tau* in the MATLAB workspace.

   The model parameters are used with the commands *tf* and *series* to create the $P_i(s)$ transfer function. The *margin* command generates a Bode plot of the system and it indicates the gain and phase stability margins as well as the phase and gain crossover frequencies.

```
% Plant transfer function
P = tf([K],[tau 1]);
% Integrator transfer function
I = tf([1],[1 0]);
% Plant with Integrator transfer function
Pi = series(P,I);
% Bode of Pi(s)
margin(Pi);
set (1,'name','Pi(s)');
```

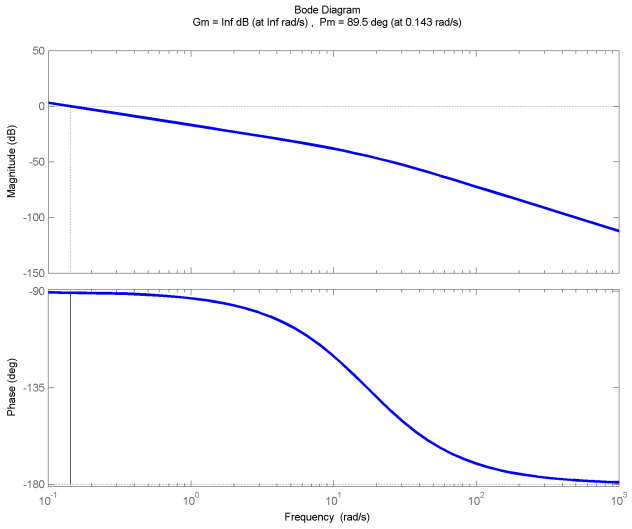



Figure 3.1.4: Bode of Pi(s) system.

2. **Find the required gain:** The gain must be determined such that the gain crossover frequency is 40.0 rad/s (use the *ginput* Matlab® command). As mentioned before, the lead compensator adds gain to the system and will increases the phase as well. Therefore, gain $K_c$ is not to be designed to meet the specified 80.0 rad/s fully.

   As given in Figure 3.1.4, the crossover frequency of the uncompensated system is 0.143 rad/s. To move the crossover frequency to 40.0 rad/s, a gain of

   $$K_c = 57 \text{ dB}$$

   or

   $$K_c = 708 \text{ V/rad}$$

   in the linear range is required. The Bode plot of the loop transfer function $H_p(s)$ (from Section 3.1.2) is given in Figure 3.1.5.

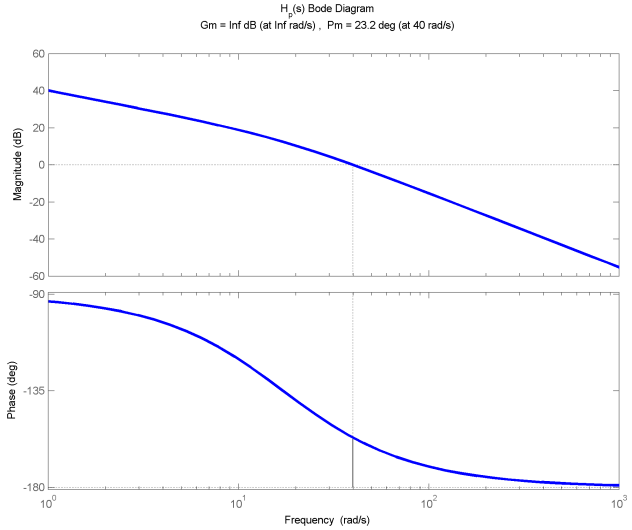



Figure 3.1.5: Bode of $H_p(s)$ system.

After the initial estimate of the gain was found, the gain was then adjusted according to the crossover frequency calculated in the generated Bode plot of the $Hp(s)$ system.

3. **Find the gain needed for specified phase margin:** Next, the gain needed to specify the phase margin of 85 degrees must be found. Also, to ensure the desired specifications are reached, we'll add another 5 degrees to the maximum phase of the lead.

   To attain the necessary phase margin, the maximum phase of the lead can be calculated using

   $$\phi_m = PM_{des} - PM_{meas} + 5$$

   Given the desired phase margin, and the phase margin of $H(s)$ is

   $$PM_{meas} = 23.2 \text{ deg}$$

   the maximum lead phase has to be about

   $$\phi_m = 66.8 \text{ deg}$$

   or

   $$\phi_m = 1.17 \text{ rad}$$

   The lead compensator, as explained in Section 3.1.2.1, has two parameters: $a$ and $T$. To attain the maximum phase $\phi_m$ shown in Figure 3.1.3, the Lead compensator has to add $20 \log_{10}(a)$ of gain. This is determined using the equation

   $$a = \frac{1 + \sin(\phi_m)}{1 - \sin(\phi_m)}$$

   The gain needed is found by inserting the max phase into this equation to get

   $$a = 23.73 \tag{3.1.8}$$

   which is

   $$20 \log 10(a) = 27.5 \text{ dB}$$

4. **Place the frequency at which the lead maximum phase occurs:** The lead maximum phase frequency must be placed at the new gain crossover frequency $\omega_{c,new}$. This is the crossover frequency after the lead compensator is applied. As illustrated in Figure 3.1.3, $\omega_m$ occurs halfway between 0 dB and $20 \log_{10}(a)$, i.e. at $10 \log_{10}(a)$. So, the new gain crossover frequency in the $H(s)$ system will be the frequency where the gain is $-10 \log_{10}(a)$.

   From Figure 3.1.5, it is found that the frequency where the $-10 \log_{10}(a)$ gain in the $H(s)$ system occurs is at about 99.6 rad/s. Thus, the maximum phase of the lead will be set to

   $$\omega_m = 110 \text{ rad/s}$$

   As illustrated earlier in Figure 3.1.3 in Section Section 3.1.2.1, the maximum phase occurs at the maximum phase frequency $\omega_m$. Parameter $T$, given by

   $$T = \frac{1}{\omega_m \sqrt{a}}, \tag{3.1.9}$$

   is used to attain a certain maximum phase frequency. This changes where the Lead compensator breakpoint frequencies $1/aT$ and $1/T$ shown in Figure 3.1.3 occur. The slope of the lead compensator gain changes at these frequencies. We can find the parameter $T$ by substituting $\omega_m = 99.6$ and the lead gain value from Equation 3.1.8 into Equation 3.1.9

   $$T = 0.0019 \text{ s/rad}$$

   Therefore, the lead breakpoint frequencies are:

   $$\frac{1}{aT} = 22.58 \text{ rad/s}$$

   and

   $$\frac{1}{T} = 535.88 \text{ rad/s}$$

5. **Create a Bode diagram of the lead compensator $G_{lead}(s)$:** Defined in Equation 3.1.5.

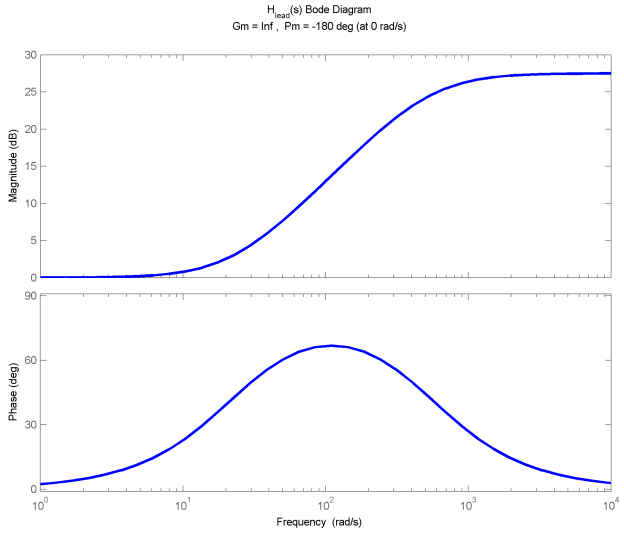



Figure 3.1.6: Bode of lead compensator $G_{lead}(s)$.

6. **Create a Bode diagram of the loop transfer function $H(s)$:** Described in Equation 3.1.7. The phase margin of $H(s)$ is 78 degrees and is below the desired phase margin of 85 degrees, as specified in Section 3.1.1.

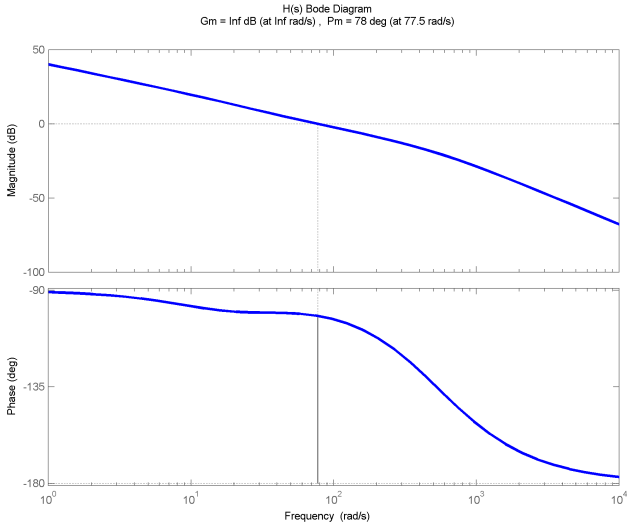



Figure 3.1.7: Bode of loop transfer function $H(s)$.

7. **Check response:** If the crossover frequency and/or phase margin specifications are not satisfied, then the lead design needs to be re-visited.

# 3.2 Pre-Lab Questions

Before you begin the lab experiments in Section 3.3, you should study the background material presented in Section 3.1, and work through the questions in this section.

1. Based on the steady-state error result of a step response from Equation 3.1.3, what type of system is the IP02 when performing speed control (Type 0, 1, or 2) and why?
2. Using the transfer function of the lead compensator Equation 3.1.6, and the error transfer function Equation 3.1.1, find the steady-state error result from a step response when the lead compensator outlined in Section 3.1.2 is used for speed control of the IP02.
3. Find the frequency response magnitude, $|P_i(\omega)|$, of the transfer function $P_i(s)$ given in Equation 3.1.4.
4. The gain crossover frequency, $\omega_c$, is the frequency at which the gain of the system is 1, or 0 dB. Express the crossover frequency symbolically in terms of the IP02 model parameters $K$ and $\tau$. Then, evaluate the expression using the nominal IP02 model parameters $K$=0.1433 m/s/V and $\tau$=0.0584 s, (or use what you found for $K$ and $\tau$ in the *IP02 Modeling Laboratory*).

# 3.3 In-Lab Exercises

The goal of this laboratory is to explore closed-loop speed control of the IP02 cart using a lead controller. You will conduct an experiment to observe the performance of the lead controller designed in Section 3.1.2.2.

## 3.3.1 Simulation

First, you will simulate the closed-loop response of the IP02 with a lead controller to a step input. Our goals are to confirm that the desired response specifications in an ideal situation are satisfied, and to verify that the motor is not saturated.

**Experiment Setup**

The s_ip02_speed Simulink diagram shown in Figure 3.3.1 is used to simulate the closed-loop speed control response with the lead controller. The *IP02 Model* subsystem uses a *Transfer Fcn* block from the Simulink library to simulate the IP02 system. The *Lead Compensator* subsystem contains the lead controller detailed in Section 3.1.2.

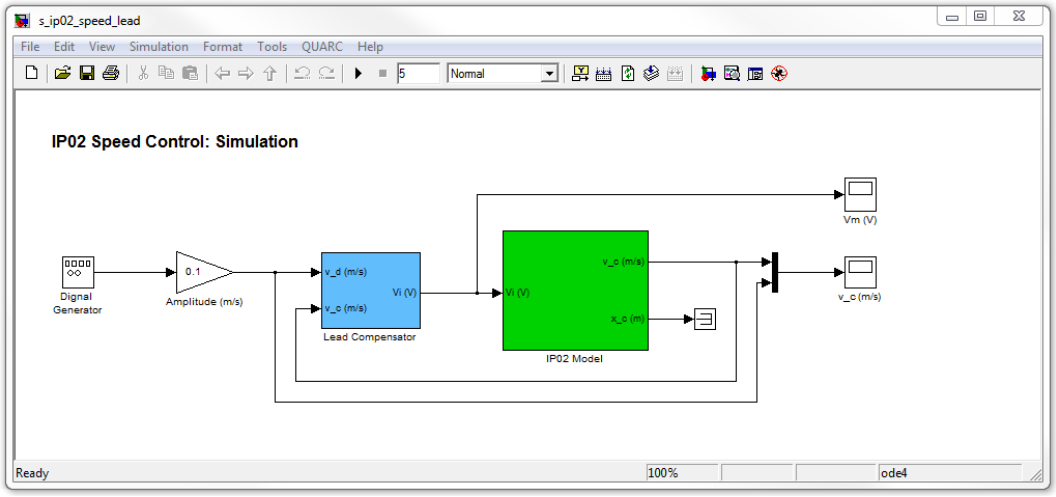



Figure 3.3.1: Simulink diagram used to simulate the IP02 closed-loop speed response

**Note:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your IP02 setup. If they have not been configured already, then go to Section 3.4.2 to configure the lab files before you begin.

1. Run the *setup_ip02_speed* script.
2. To generate a step reference, ensure the *Signal Generator* is set to the following:
   - Signal type = *square*
   - Amplitude = 1
   - Frequency = 0.5 Hz
3. In the Simulink diagram, set the *Amplitude (m/s)* gain block to $0.1$ to generate a step with an amplitude of 0.2 meters/second (i.e., square wave goes between $\pm 0.1$ m which results in a step amplitude of $0.2$ m).
4. Open the cart speed scope, *v_c (m/s)*, and the motor input voltage scope, *Vm (V)*.
5. Start the simulation. By default, the simulation runs for 5 seconds. The scopes should be displaying responses similar to figures 3.3.2 and 3.3.3. Note that in the *v_c (m/s)* scope, the purple trace is the setpoint position while the yellow trace is the simulated position (generated by the *IP02 Model* block).

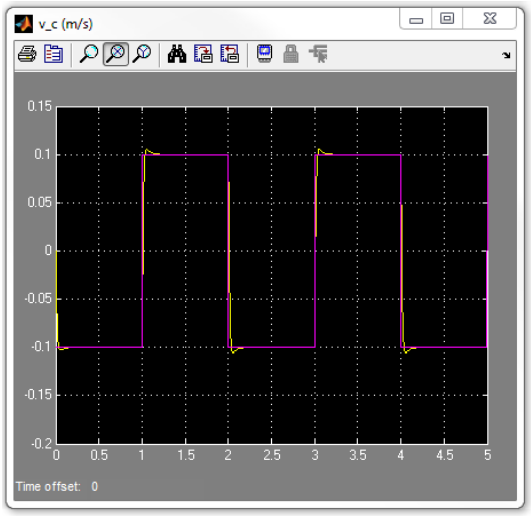



Figure 3.3.2: Ideal lead speed response.

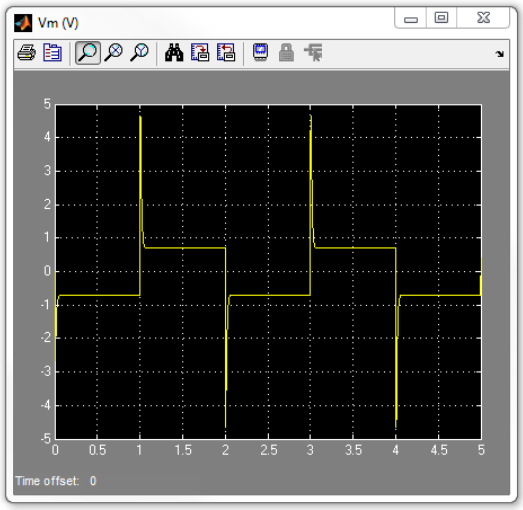



Figure 3.3.3: Ideal lead motor input voltage.

6. Varify that the time-domain specifications in Section 3.1.1 are satisfied and that the motor is not being saturated. To calculate the steady-state error, peak-time, and percent overshoot, use the simulated response data stored in the *data_v* variable.
7. If the specifications are not satisfied, go back in the lead compensator design. You may have to, for example, add more maximum phase in order to increase the phase margin. If the specifications are met, move on to the next step.
8. Generate a MATLAB figure showing the *Simulated Lead* speed response and its input voltage.

## 3.3.2 Implementing LEAD Speed Control

In this section, the speed of the IP02 cart is controlled using the lead compensator. Measurements will then be taken to ensure that the specifications are satisfied.

**Experiment Setup**

The q_ip02_speed Simulink diagram shown in Figure 3.3.4 is used to implement the speed control experiments. The *IP02 Speed* subsystem contains QUARC blocks that interface with the DC motor and sensors of the IP02 system, as discussed in the QUARC Integration Lab Section A. The *Lead Control* subsystem implements the lead controller detailed in Section 3.1.2, except a high-pass filter is used to obtain the velocity signal (as opposed to taking the direct derivative).

**Note:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your IP02 setup. If they have not been configured already, then go to Section 3.4.2 to configure the lab files before you begin.

1. Run the *setup_ip02_speed* script.
2. Enter the $K_c$, $a$, and $T$ parameters found in Section 3.1.2.2.
3. Set Signal Type in the *Signal Generator* to *square* to generate a step reference.
4. Set the *Amplitude (m/s)* gain block to $0.1$ to generate a step with an amplitude of 0.2 meters.
5. Open the cart speed scope, *Meas.(0) and Sim.(1) Resp.*, and the motor input voltage scope, *Vm (V)*.
6. Click on QUARC | Build to compile the Simulink diagram.

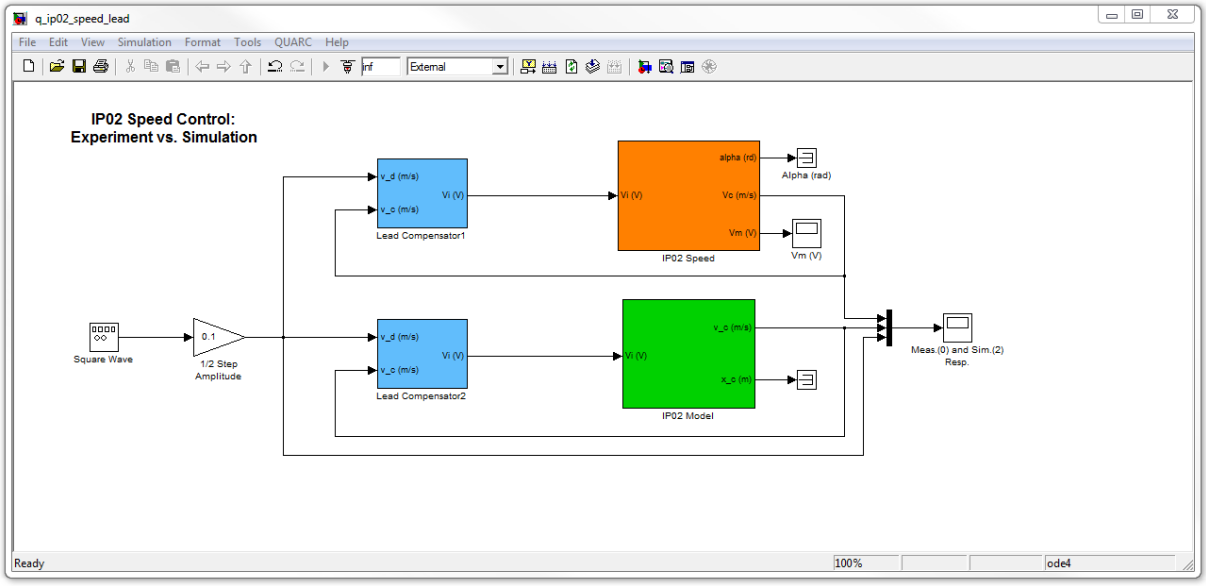



Figure 3.3.4: Simulink diagram used with QUARC to run the lead controller on the IP02

7. Select QUARC | Start to begin running the controller. The scopes should display responses similar to figures 3.3.5 and 3.3.6. Note that in the *Meas.(0) and Sim.(1) Resp.* scope, the yellow trace is the measured position, the purple trace is the simulated position, and the cyan trace is the setpoint.

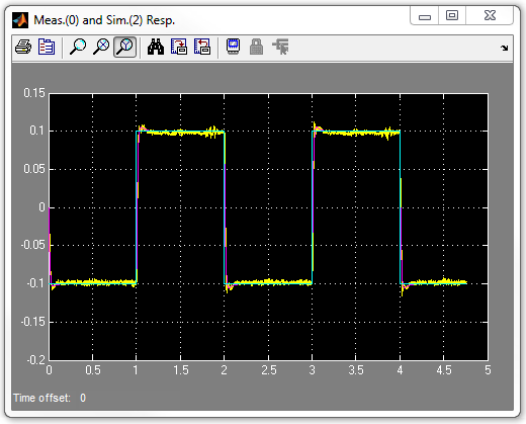



Figure 3.3.5: Measured and Simulated lead step response.

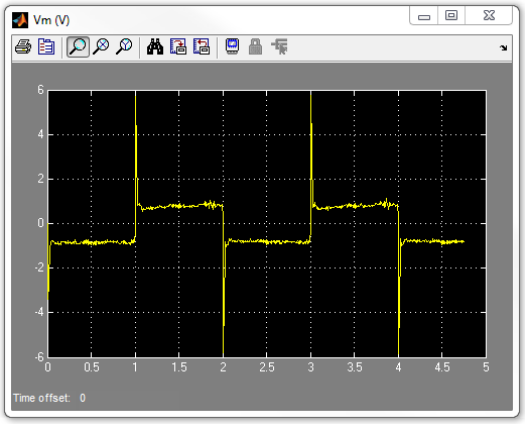



Figure 3.3.6: Lead control input voltage.

8. When a suitable response is obtained, click on the Stop button in the Simulink diagram toolbar (or select QUARC | Stop from the menu) to stop running the code.

9. Generate a MATLAB figure showing the measured speed response and its input voltage. As in the *s_ip02_speed* Simulink diagram, when the controller is stopped each scope automatically saves its response to a variable in the MATLAB workspace. Thus, the *Meas.(0) and Sim.(2) Resp.* scope saves its response to the *data_v* variable and the *Vm (V)* scope saves its data to the *data_vm* variable.

10. Measure the steady-state error, the percent overshoot, and the peak time of the IP02. Does the response satisfy the specifications given in Section 3.1.1?

11. Do the experimental results match the simulated model response? Give some possible reasons why discepencies may exist.

12. Click the Stop button on the Simulink diagram toolbar (or select QUARC | Stop from the menu) to stop the experiment.
13. Turn off the power to the amplifier if no more experiments will be performed on the IP02 in this session.

# 3.4 System Requirements

Before you begin this laboratory make sure:

- QUARC® is installed on your PC, as described in Reference [3].
- You have a QUARC compatible data-aquisition (DAQ) card installed in your PC. For a listing of compliant DAQ cards, see Reference [1].
- IP02 and amplifier are connected to your DAQ board as described Reference [2].

## 3.4.1 Overview of Files

| File Name | Description |
|---|---|
| IP02 Speed Control Workbook (Student).pdf | This laboratory guide contains pre-lab and in-lab exercises demonstrating speed control of the Quanser IP02 linear plant. The in-lab exercises are explained using the QUARC software. |
| setup_ip02_speed.m | The main Matlab® script that sets the IP02 speed control parameters. **Run this file only to setup the laboratory.** |
| s_ip02_speed_lead.mdl | Simulink file that simulates the closed-loop IP02 lead speed control step response. |
| q_ip02_speed_lead.mdl | Simulink file that implements the closed-loop IP02 lead speed controller using QUARC. |

Table 3.4.1: Files supplied with the IP02 Speed Control Laboratory.

## 3.4.2 Configuring the IP02 and the Lab Files

Before beginning the lab exercises the IP02 device, the q_ip02_speed_lead Simulink diagram and the setup_ip02_speed.m script must be configured.

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

1. Set up the IP02 without the additional weight as described in [2].
2. Load the Matlab® software.
3. Browse through the Current Directory window in Matlab® and find the folder that contains the IP02 modeling files, e.g. q_ip02_speed.mdl.
4. Double-click on the q_ip02_speed.mdl file to open the Simulink diagram shown in Figure Figure 3.3.4.
5. **Configure DAQ:** Double-click on the HIL Initialize block in the Simulink diagram and ensure it is configured for the DAQ device that is installed in your system. For instance, the block shown in Figure 3.3.4 is setup for the Quanser Q2-USB hardware-in-the-loop board. See the QUARC Installation Guide [3] for more information on configuring the HIL Initialize block.
6. Go to the *Current Directory* window and double-click on the setup_ip02_speed.m file to open the setup script for the q_ip02_speed Simulink model.

7. **Configure setup script:** The beginning of the setup script is shown below. Ensure the script is setup to match the configuration of your actual IP02 device. For example, the script given below is setup for an IP02 plant without the additional weight and it is actuated using the Quanser VoltPAQ device with a gain of 1. See the IP02 User Manual [2] for more information on IP02 plant options and corresponding accessories.
   Finally, make sure MODELING_TYPE is set to 'MANUAL'.

```
% ############### IP02 CONFIGURATION ###############
% Type of Cart Load: set to 'NO_LOAD', 'WEIGHT'
IP02_LOAD_TYPE = 'NO_LOAD';
% IP02_LOAD_TYPE = 'WEIGHT';
% Turn on or off the safety watchdog on the cart position: set it to 1 , or 0
X_LIM_ENABLE = 1;       % safety watchdog turned ON
%X_LIM_ENABLE = 0;      % safety watchdog turned OFF
% Safety Limits on the cart displacement (m)
X_MAX = 0.35;            % cart displacement maximum safety position
X_MIN = - X_MAX;        % cart displacement minimum safety position
% Amplifier Gain used: set VoltPAQ to 1
K_AMP = 1;
% Amplifier Type: set to 'VoltPAQ' or 'Q3'
AMP_TYPE = 'VoltPAQ';
% Digital-to-Analog Maximum Voltage (V); for Q4/Q8 cards set to 10
VMAX_DAC = 10;

% ############### USER-DEFINED CONTROLLER DESIGN ###############
% Type of Controller: set it to 'LEAD', or 'MANUAL'
%CONTROLLER_TYPE = 'LEAD';    % LEAD controller design: automatic mode
CONTROLLER_TYPE = 'MANUAL';    % controller design: manual mode

%CONTROLLER_TYPE = 'PI'; % PI controller design: automatic mode
```

8. Run the script by selecting the Debug | Run item from the menu bar or clicking on the *Run* button in the tool bar.

# LAB REPORT

This laboratory contains three groups of experiments, namely,

1. Linear Servo Modeling,
2. Position Control, and
3. Speed Control.

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 4.4 you can find some basic tips for the *format* of your report.

## 4.1 Template for Modeling Report

**I. PROCEDURE**

1. *Implementation*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure in Step 10 in Section 1.3.1.
   - Briefly describe the experimental procedure in Step 14 in Section 1.3.1.

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

1. Response plot from step 13 in Section 1.3.1, *Model and experimental comparison*.

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

1. The model parameters $B_{eq}$, $A_m$, $J_{eq}$, $K$, and $\tau$ in Step 11 in Section 1.3.1.

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

1. Why the nominal model does not represent the IP02 with better accuracy in Step 13 in Section 1.3.1.

# 4.2 Template for Position Control Report

**I. PROCEDURE**

1. *Simulation*
    - Briefly describe the main goal of the simulation.
    - Briefly describe the simulation procedure and observations in Step 7 in Section 2.3.1.
    - Briefly describe the simulation procedure and observations in Step 8 in Section 2.3.1.
2. *Implementation*
    - Briefly describe the main goal of this experiment.
    - Briefly describe the experimental procedure in Step 9 in Section 2.3.2.
    - Briefly describe the proposed changes in Step 12 in Section 2.3.2.

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

1. Ideal position response plot from 10 in Section 2.3.1, *Position control simulation*.
2. Ideal position response plot from 9 in Section 2.3.2, *Position control implementation*.

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

1. Peak time, percent overshoot, steady-state error, and input voltage in Step 11 in Section 2.3.1.
2. Peak time, percent overshoot, steady-state error, and input voltage in Step 10 in Section 2.3.2.
3. Explanation of the simulation and implementation response comparison in Step 11 in Section 2.3.2.

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

1. Whether the controller meets the specifications in Step 11 in Section 2.3.1, *Position controller simulation*.
2. Whether the controller meets the specifications in Step 10 in Section 2.3.2, *Position controller implementation*.

# 4.3 Template for Speed Control Report

**I. PROCEDURE**

1. *Simulation*
    - Briefly describe the main goal of the simulation.

2. *Implementation*
    - Briefly describe the main goal of this experiment.
    - Briefly describe the experimental procedure in Step 9 in Section 3.3.2.

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

1. Simulated Lead speed response plot from 8 in Section 3.3.1, *Speed control simulation*.
2. Lead speed response plot from 9 in Section 3.3.2, *Speed control implementation*.

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

1. Peak time, percent overshoot, steady-state error, and input voltage in Step 6 in Section 3.3.1.
2. Peak time, percent overshoot, steady-state error, and input voltage in Step 10 in Section 3.3.2.
3. Explanation of the simulation and implementation response comparison in Step 11 in Section 3.3.2.

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

1. Whether the controller meets the specifications in Step 6 in Section 3.3.1, *Speed controller simulation*.
2. Whether the controller meets the specifications in Step 10 in Section 3.3.2, *Speed controller implementation*.

# 4.4 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.

# APPENDIX A.0

# IP02 QUARC INTEGRATION

In this section, we explain how to send voltage commands to the Quanser® IP02 and measure the position of the cart and pendulum in real-time using your computer.

**Prerequisites**

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

- The required software and hardware outlined in Section 1.4, Section 2.4 or Section 3.4.
- Basics of QUARC®.

---

# A.1 Applying Voltage to IP02 Motor

Here are the basic steps to apply a voltage to the IP02 motor using QUARC®:

1. Make a Simulink® model that interacts with your installed data-acquisition device using blocks from the *QUARC Targets* library. This is explained in Section Section A.1.1,
2. From the Simulink® model, build real-time code as shown in Section Section A.1.2, and
3. Execute the code as explained in Section Section A.1.3.

## A.1.1 Making the Simulink Model

In this section, we will make a Simulink® model as shown in Figure A.1.1 using QUARC® blocks to feed a sinusoidal voltage to the IP02 DC motor. The blocks from the *QUARC Targets* library are used to interact with a data-acquisition board, e.g. Quanser Q2-USB or Q8-USB device.

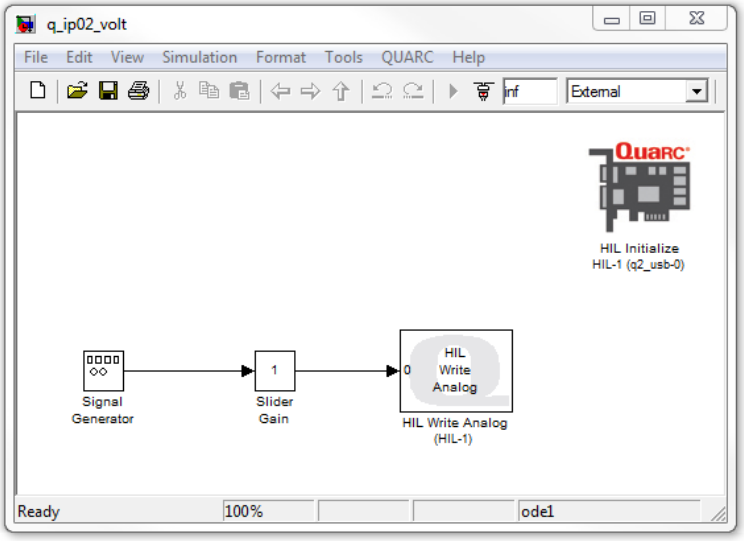



Figure A.1.1: Simulink model used with QUARC to apply voltage to IP02

Follow these steps to make the Simulink® diagram:

1. Load the Matlab® software.
2. Create a new Simulink® diagram. To do this, go to File | New | Model item in the menu bar.
3. Open the Simulink Library Browser window by clicking on the View | Library Browser item in the Simulink menu bar or clicking on the Simulink icon.
4. Expand the *QUARC Targets* item and go to the Data Acquisition | Generic | Configuration folder, as shown in Figure A.1.2.

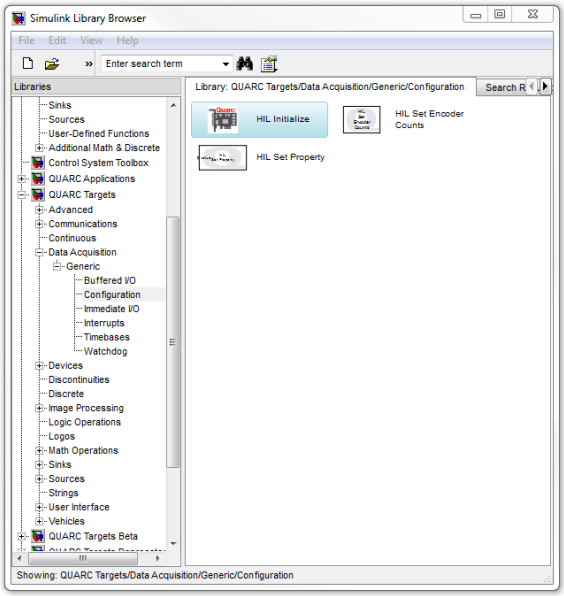



Figure A.1.2: *QUARC Targets* in Simulink® Library Browser

5. Click-and-drag the *HIL Initialize block* from the library window into the blank Simulink® model. This block is used to configure your data-acquisition device, e.g. the Quanser Q2-USB or Q8-USB hardware-in-the-loop (HIL) boards.

6. In the Library Browser, go to the Data Acquisition | Generic | Immediate I/O category. This contains various blocks used to interact with actuators and sensors.

7. Click-and-drag the *HIL Write Analog* block from the library into the Simulink® diagram. This block is used to output a voltage from an Analog Output channel, i.e. digital-to-analog (D/A) channel, on the data-acquisition device.

8. Add the *Signal Generator* block, found in the Simulink® | Source folder, and the *Slider Gain* block, from the Simulink® | Math Operations category, into the Simulink® model. Connect the blocks as shown in A.1.1.

9. Double-click on the *HIL Initialize* block:

   - In the *Board type* field, select the board that is installed in your PC. For example, if you have a Quanser Q2-USB board then select *q2_usb*.
   - If more than one of the same board is installed (e.g. two Q2-USB devices), ensure the *Board number* field is set correctly, e.g. if two boards are used, then choose either 0 or 1.

10. Go to the *Analog Output* pane shown in Figure A.1.3. Make sure the *Analog output channels* field includes 0. This will ensure 0 V is output from Analog Output channel #0 when the QUARC controller is stopped. For more information, click on the *Help* button. Otherwise, click on the OK button and proceed.

    **Note:** If you are using a NI DAQ device, make sure you enter [0] in the Analog Output channel box. The analog output channels for the NI boards are not selected by default.

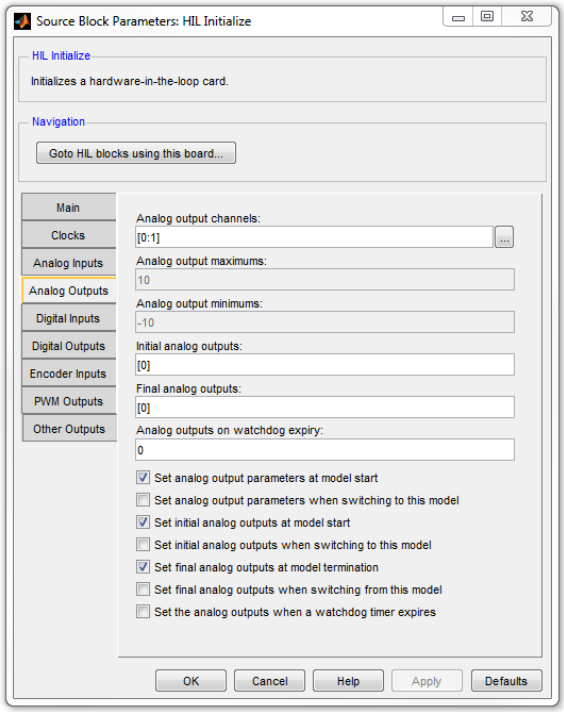



Figure A.1.3: Configuring Analog Output channel on DAQ device

11. Double-click on the *HIL Write Analog* block.
    - Make sure *Board name* is set to HIL-1 (i.e. points to the HIL Initialize block).
    - Set *Channels* to 0 (default setting). Recall that, as instructed in Reference [2], the DC motor is connected to Analog Output Channel #0 on the hardware-in-the-loop board. Therefore, *Channels* should be set to 0.
    - Set *Sample time* to -1 (default setting). This implies that the sampling interval is inherited from the previous block.
12. Click on the OK button to save and close the *HIL Write Analog* block properties.
13. Save the Simulink® mode by selecting the File | Save item in the menu bar or clicking on the Save icon.

## A.1.2 Compiling the Model

The Simulink® model we made in Section Section A.1 can now be used by QUARC to generate code. When you execute this code, a voltage is sent to the IP02.

Follow these steps to generate code from a Simulink® diagram:

1. In the Simulink® diagram made in Section Section A.1, go to the QUARC | Set default options item to set the correct Real-Time Workshop parameters and setup the Simulink® model for external use (as opposed to the simulation mode).
2. To view the compiler options shown in Figure A.1.4, go to QUARC | Options in the Simulink® model tool bar.

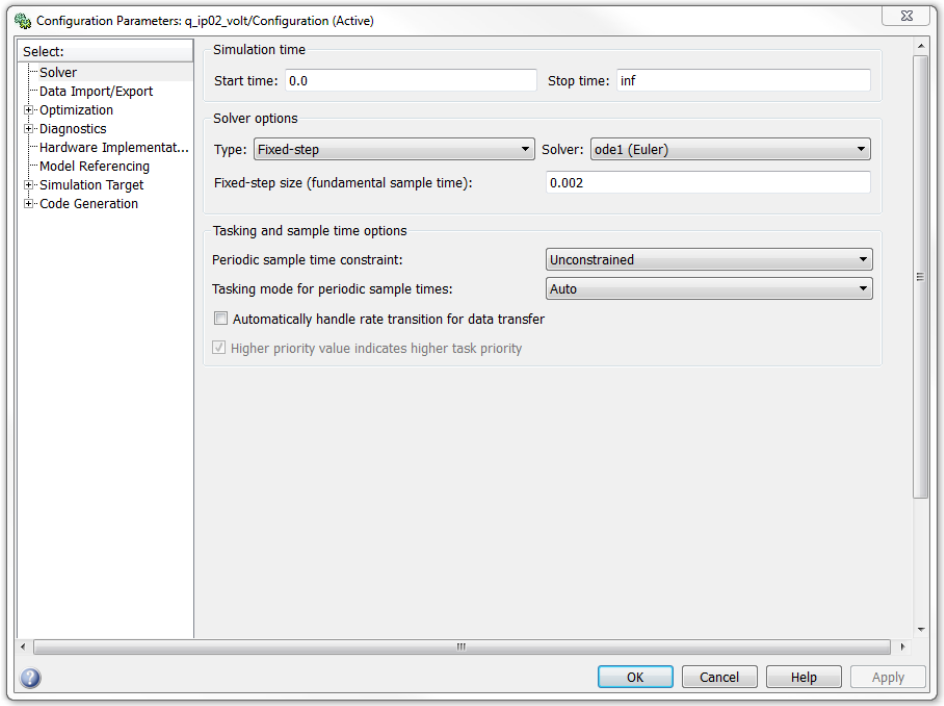



Figure A.1.4: Default QUARC solver settings

3. Real-Time Workshop pane:
   - *System target file* is set to Target Language Compiler file quarc_windows.tlc.
   - *Make command* is set to make_rtw and the *Template makefile* is set to quarc_default_tmf file.
4. Solver pane:
   - *Stop time* is set to *inf* in order for the code to be executed continuously until it is stopped manually by the user. Alternatively, the *Stop time* parameter can be set to the desired duration (code will cease executing when the stop time value is reached).
   - *Type* parameter is set to Fixed-step. When compiling real-time code, the solver must be fixed-step as opposed to variable step which can be used in simulations.
   - *Solver* is set to discrete. There are no continuous blocks inside the designed Simulink® model, therefore having a discrete solver is fine. However, if an Integrator block or another continuous system were be added, then the Solver field would have to be changed to an integration method such as *ode1 (Euler)*.
   - *Fixed-step size* field sets the sampling interval, or sampling time, of the controller. By default this is set to 0.002 seconds, which is a sampling rate of 500 Hz.
5. Click on the OK button to close the Configuration Parameters window.
6. Select the QUARC | Build item. Various lines in the Matlab® Command Window should be displayed as the model is being compiled.
7. Once done compiling, a QUARC Windows executable file along with a folder containing various "C" and Matlab® files are generated. Note that once the executable is created, the folder is no longer needed. If you like, you can remove the executable and associated code folder may be removed from the current directory by clicking on QUARC | Clean item.

See [1] for more information about configuring QUARC®.

## A.1.3 Running QUARC Code

Once the Simulink® model has been compiled, the code can be executed and the voltage set in the Simulink® model can be sent to the SRV02 motor. Here are the steps to follow:

1. Power ON your power amplifier (e.g. Quanser VoltPAQ).
2. To begin executing the code, click on the QUARC | Start item in the Simulink® model. The IP02 cart should begin moving back-and-forth. This command actually does two things: it connects to the target and then executes the code. Alternatively, users may decide to go through these steps individually:

   **Option 1:** In the Simulink® model tool bar, click on the *Connect to target* icon and then click on the *Run* icon. These buttons are shown in Figure A.1.5.

   **Option 2:** Select the Simulation | Connect to target item from the menu bar and the select Simulation | Start Real-Time Code item.


Figure A.1.5: Simulink® model toolbar: connect to target and compilation

3. Double-click on the Signal Generator block to open its parameter window.
4. Set the *Frequency* field to 0.5 Hz and click on the OK button. Notice how the parameter change effects the IP02 immediately: the velocity of the cart begins to switch back-and-forth slowly.
5. Vary the value of the Slider Gain block between 0 and 2. Examine how the speed of the IP02 cart changes proportionally with the amplitude of the sine wave.
6. Select the QUARC | Stop item to stop the code execution (or click on the Stop button in the Simulink® model tool bar).
7. Power OFF the amplifier if no more experiments will be run in this session.

# A.2 Measuring Position using Encoder

The Simulink® diagram designed previously is modified to include an encoder measurement, as illustrated in Figure A.2.1 below.

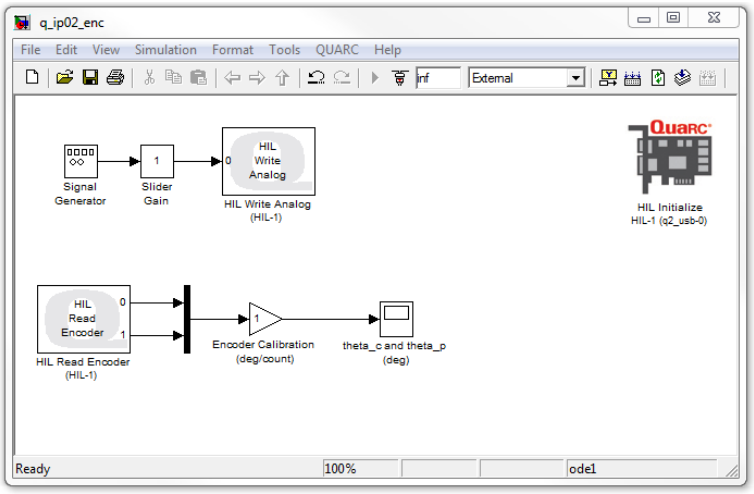



Figure A.2.1: Simulink® model used with QUARC to send voltage to IP02 and read the encoder sensors.

Using the Simulink® model designed in Section A.1, follow this procedure to add encoder functionality:

1. From the QUARC Targets | Data Acquisition | Generic | Immediate I/O category in the Library Browser, add a HIL Read Encoder block.
2. Recall that, as instructed in [2], the cart encoder is connected to Encoder Input #0 and the pendulum encoder is connected to Encoder Input #1 on the data acquisition board. The HIL Read Encoder block is configured for to read channel 0 by default, and should be changed to read both encoders by updating the *Channels:* field to "[0 1]". The default encoder configurations in the HIL Initialize block are fine (but keep in mind that these can be changed).
3. Add two Scope and Gain blocks from the *Math Operations* folder in the Library Browser, into the Simulink® model.
4. Add a Mux block from the Signal Routing folder in the Library Borwser.
5. Connect the Scope and Gain blocks as depicted in Figure A.2.1.
    - Connect the HIL Read Encoder block outputs to the Mux, followed by the Gain block. Label the gain *Encoder Calibration (deg/count)*.
    - Connect the output of this gain block to the input of the Scope block and label the scope *theta_c and theta_p (deg)*. This scope will display the measured angular position of the cart and pendulum in degrees.
6. Set the *Frequency* parameter in the Signal Generator block to 1.0 Hz and the Slider Gain block to 1.
7. Open the *Vm (V)* and *theta_c and theta_p (deg)* scopes.
8. Save the Simulink® model (you may want to save the model as a different file).
9. Power ON the power amplifier.
10. Go to QUARC | Build to compile the code.

11. Click on QUARC | Start to execute the code. As the IP02 cart moves back-and-forth, the *theta_c and theta_p (deg)* should display the encoder readings. Rotate the pendlum shaft to ensure that the pendulum encoder is functioning correctly. Since the *Encoder Calibration (deg/count)* gain has not been configured yet, the scope is displaying the number of counts from the encoder output, which is proportional to the position of the encoder shaft.

    **Note:** The measurement will be very large. Click on the Autoscale icon in the scope to zoom out and view the entire signal. Alternatively, the y-range of the scope can be set manually. To do this, right-click on the y-axis, select Axes Properties from the drop-down menu, and set the desired y-range values.

12. As discussed in the *IP02 User Manual* [2], the encoder outputs 4096 counts for every full revolution. To measure the load gear angle, set the *Encoder Calibration (deg/count)* gain block to 360 / 4096 degrees per count.

13. The measurement will be very small. Click on the *Autoscale* icon in the scope to zoom up on the signal or adjust the range of the y-axis manually. The position scope should appear similarly as shown in Figure A.2.2. Note that no further calibration is needed since the encoder positions increase when the input voltage goes positive or the pendulum encoder is rotated CCW.

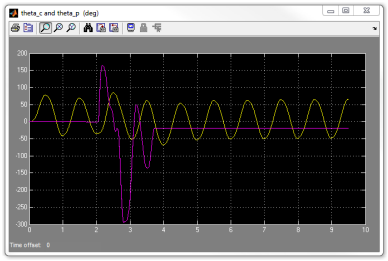


Figure A.2.2: Position reading using encoder.

14. Select the QUARC | Stop item to stop the code from running.

15. Power OFF the amplifier if no more experiments will be run in this session.

# A.3 Saving Data

The scopes in the Simulink® model can be configured to save variables in the Matlab® workspace. For instance, to configure the position scope *theta_c and theta_p (deg)* in the Simulink® model from Section Section A.2 perform the following:

1. Open the *theta_c and theta_p (deg)* scope.
2. Click on *Parameters* icon and select the *Data History* tab, as shown in Figure A.3.1.
   - Select the *Save data to workspace* check box.
   - Set the *Variable name* field to a desired variable, e.g. *theta_data*.
   - Set Format to Array.

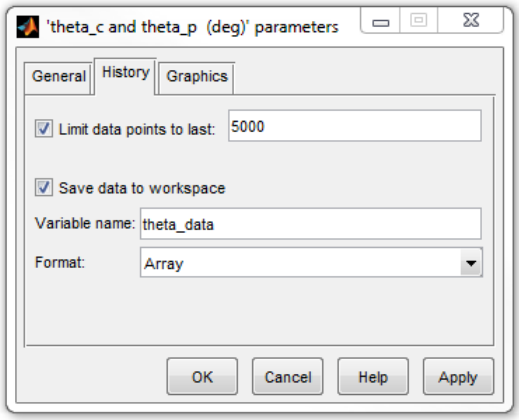



Figure A.3.1: Adjusting scope parameters to save data

**Note:** By default, the Limit data points to last box is set to 5000. This means that only the last 5000 points of data will be saved in the variable. Thus, given that the controller runs at 500 Hz, this implies that the last 10 seconds of data shown in the *theta_l (deg)* scope will be captured.

3. Click on the OK button.
4. Save the Simulink® model.
5. Select QUARC | Build to rebuild the model.
6. Click on QUARC | Run.
7. Run the controller for a few seconds and stop QUARC.
8. When the controller is stopped, the variable *theta_data* is saved to the workspace. The variable is a three-dimensional array with a maximum of 5000 elements. The first vector is the running time and the second vector is the position of the cart, and the third vector is the position of the pendulum. You can plot the data into a Matlab figure using a script like:

```
t = theta_data(:,1);
th_c = theta_data(:,2);
th_p = theta_data(:,3); plot(t,th_c);
hold on
plot(t,th_p,'r');
```

You can then add Matlab® commands such as *xlabel*, *ylabel*, and *title* to desribe the data and units you are plotting.

**Note:** If the controller has not run for the full 10 seconds then, it will have $t_f/T_s$ number of elements, where $t_f$ is the duration of the controller and $T_s$ is the sampling interval. For instance, if you ran QUARC for 4 seconds then there will be $4/0.002 = 2000$ elements.

9. Running the script generates a Matlab figure as shown in Figure A.3.2.

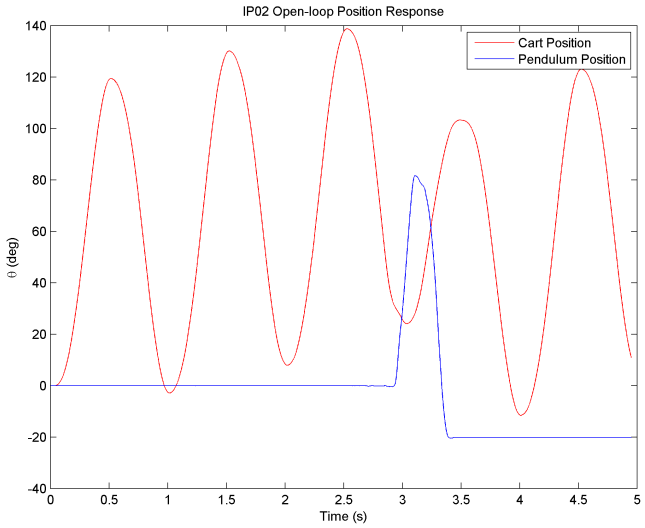



Figure A.3.2: Plotting saved data

**Note:** Use the Matlab® command *ginput* to measure points directly from the Matlab figure.

There are many different ways to save data for offline analysis, e.g. saving data to a Matlab MAT file. Go to [1] in the QUARC Basics | Data Collection category for more information.

# A.4 Instructor's Guide

Every laboratory in this manual is organized into four parts:

Background section provides all the necessary theoretical background for the experiments. Students should read this section first to prepare for the Pre-Lab questions and for the actual lab experiments.

Pre-Lab Questions section is not meant to be a comprehensive list of questions to examine understanding of the entire background material. Rather, it provides targetted questions for preliminary calculations that need to be done prior to the lab experiments.

Lab Experiments section provides step-by-step instructions to conduct the lab experiments and to record the collected data. The lab may also include a set of pre-lab questions that need to be done prior to the lab experiments.

System Requirements section describes all the details of how to configure the hardware and software to conduct the experiments. It is assumed that the hardware and software configuration have been completed by the instructor or the teaching assistant *prior* to the lab sessions. However, if the instructor chooses to, the students can also configure the systems by following the instructions given in this section.

Assessment of ABET outcomes is incorporated into this manual as shown by indicators such as . These indicators correspond to specific performance criteria for an outcome.

## A.4.1 Pre-lab Questions and Lab Experiments

### A.4.1.1 How to use the pre-lab questions

All or some of the questions in the Pre-Lab Questions sections can be assigned to students as homework. One possibility is to assign them as a homework one week prior to the actual lab session and ask the students to bring their assignment to the lab session. This would help them get ready for the lab session. You should encourage them to study the background section of the chapter prior to attempting the pre-lab questions. **Note** that solutions for some of the Pre-Lab questions are parameters needed for the experiments in the lab session.

Another possibility is to go over some of these questions either in class or in the lab session together with the students. This could generate an interactive learning opportunity for them prior to the lab.

Finally, it is possible to use some of the pre-lab questions in your mid-term or final exams. This would reinforce the concepts covered in the labs; connections between the abstract theory and the real hardware; and would give you an option to integrate some of the work done in the lab sessions into your exams.

### A.4.1.2 How to use the laboratory experiments

This manual is organized into several laboratory sections. Each section contains several experiments which are, for the most part, independent of each other. Therefore, one possible way to use this material is to conduct the individual experiments in your weekly lab sessions. Another possibility is to divide the class into teams and have each team conduct an experiment given in a section.

## A.4.2 Assessment for ABET Accreditation

In the United States, accreditation is a peer-review process. Educational institutions or programs volunteer to undergo this review periodically to determine if certain criteria are being met. The *Accreditation Board for Engineering and Technology*, ABET, is responsible for the specialized accreditation of educational programs in applied science, computing, engineering, and technology. ABET accreditation is assurance that a college or university program meets the quality standards established by the profession for which it prepares its students.

It is the responsibility of the program seeking accreditation to demonstrate clearly that the program meets a set of criteria. One of these criteria is the ``Criterion 3: Program Outcomes''. Engineering programs must demonstrate that their students attain program outcomes (a) through (k). Much more information about this can be found in the ``Criteria for Engineering Accreditation'' document ABET publishes on its website annually (http://www.abet.org).

For fulfillment of Criterion 3, a program must show that there is an assessment and evaluation process in place that periodically documents and demonstrates the degree to which the program outcomes are attained by their students. Most programs do this by mapping the outcomes (a) through (k) to the courses in the curriculum[1]. Then, these outcomes are assessed in the courses. Finally, the assessment results are collected from the courses and compiled into program-level data to demonstrate the ``degree to which the program outcomes are attained by their students''.

If your course is part of a similar assessment effort in your program, you probably need to assess the following outcomes in your course:

(A) An ability to apply knowledge of mathematics, science, and engineering,

(B) An ability to design and conduct experiments, as well as to analyze and interpret data,

(G) An ability to communicate effectively, and

(K) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

These outcomes can be assessed in your course using various assessment tools, such as student surveys and

assignments or questions targeting specific outcomes. To measure achievement of an outcome (such as outcome ``A'' in the list above), typically some performance criteria are defined for the outcome. The *performance criteria* are a set of measurable statements to define each learning outcome. They identify the specific knowledge, skills, attitudes, and/or behavior students must demonstrate as indicators of achieving the outcome.

For the purpose of this laboratory curriculum, we defined a set of performance criteria for each outcome. These criteria are labeled as ``A-1, A-2, B-3, ..., K-3'' as indicated in the rubrics in Section A.4.3 below. We also embedded these performance criteria in the curriculum shown by indicators such as .

### A.4.2.1 Assessment in your course

Assessment of outcomes is different than grading. A course grade (or a grade on an assignment or exam), is a composite indicator. For example, if a student receives "B" as a grade in your course, it is probably difficult to tell his/her level of achievement in outcome "A" versus "G". One of the purposes of assessment is to "measure" the level of achievement of these specific skills and knowledge so that improvements can be made in the future offerings of the course.

**So, how should you introduce outcomes assessment into your course?** The outcomes assessment approach described here can be applied to *each* pre-lab homework assignment and lab report of *each* student throughout the semester. This may or may not be feasible depending on your class size. In general, a *representative sample* of student work is assessed.

You can continue to give assignments/exams and grade them in the traditional way. To introduce assessment into your course, you can pick a representative sample of student work and "score" their work using the scoring sheets and rubrics given in this manual. This is a good way to start introducing assessment into your course.

Recall that for fulfillment of Criterion 3, a program must ``document'' the assessment process. Programs collect sample student work in the academic year prior to the site visit by an ABET team. You can retain the sample homeworks, lab reports, their scoring sheets and the assessment workbook as ``evidence'' for the ongoing assessment effort in your course. This collection can then be given to the assessment committee in your program to be incorporated into the program-level evidence they will compile prior to the ABET site visit.

### A.4.2.2 How to score the pre-lab questions

If you choose to assign the pre-lab questions as homework, then the outcome targetted by these questions can be assessed using the student work. The pre-lab questions require students to ``apply'' their math and engineering science knowledge through calculations and problem solving strategies. Therefore, outcome ``A'' was mapped to the pre-lab questions through its performance criteria.

If you assign the pre-lab questions as homework, you can ``score'' the returned homeworks using the rubric for outcome ``A'' given in Section A.4.3 and the scoring sheet provided for that pre-lab in that chapter.

To score homework of *one* student:

1. Print the scoring sheet for the Pre-Lab Questions section you assigned as homework. One sheet is used per student.
2. Use the rubric for ``Outcome A'' (Section A.4.3) to assign a score for each question. The rubric gives the description of ``levels of achievement'' (4 = exemplary, 3 = proficient, 2 = developing and 1 = beginning/incomplete) for each criterion. As an example, below is a completed sample scoring sheet after evaluating the homework of one student.

[1] Disclaimer: The opionions expressed or the assessment techniques described here have not been endorsed by ABET in any way.

| Question | A-1 | A-2 | A-3 |
|---|---|---|---|
| 1 | 3 | 2 | |
| 2 | 4 | 2 | |
| 3 | | 3 | |
| 4 | | 3 | |
| 5 | | 4 | |
| 6 | | 3 | |
| 7 | | 3 | |
| 8 | | 3 | |
| 9 | 3 | 3 | |
| 10 | | 3 | 4 |
| 11 | | 3 | 4 |
| Total | 10 | 32 | 8 |

3. You can then enter the ``Total'' for each performance criterion into the assessment workbook [4] as shown in Figure A.4.1.

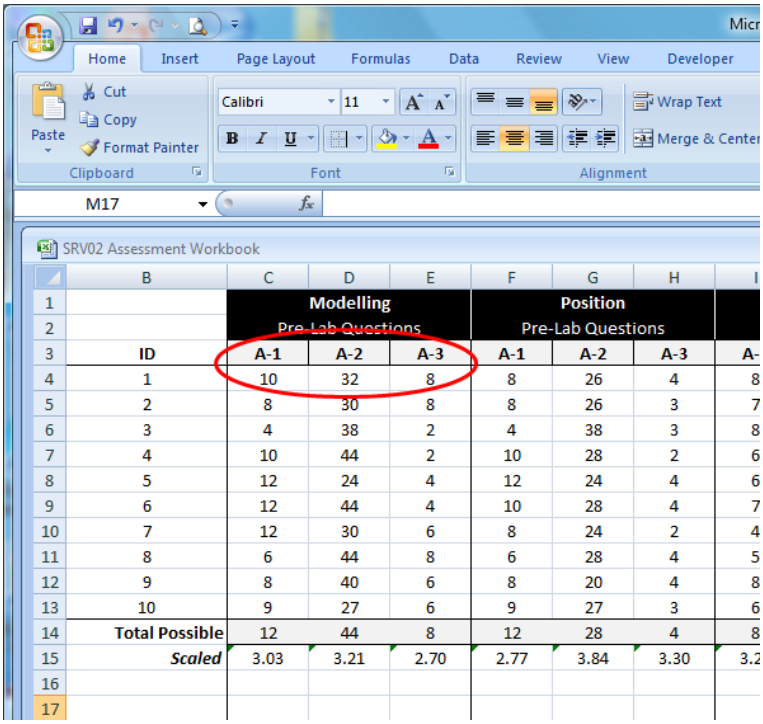



Figure A.4.1: Pre-Lab entry into the assessment workbook for one student.

## A.4.2.3 How to score the lab reports

As mentioned earlier in Section A.4.1.2, there are various ways in which you can use the material provided in this manual. In any case, the outcomes targetted by the lab experiments can be assessed from the lab reports submitted by the students. These reports should follow the specific template for content given at the end of each laboratory chapter. This will provide a basis to assess the outcomes easily.

The lab activities correspond to the ``applied'' part of engineering. Therefore, outcomes ``B'' and ``K'' were mapped to the lab activities through their performance criteria. The lab reports themselves match outcome ``G'' on effective communication skills.

If you choose to do an individual experiment in your weekly lab sessio then you can ask the students to submit a lab report using the report template provided for this experiment. The template contains the main ``content'' sections you would expect in a typical lab report (procedure, results, analysis, conclusions). Each section of the report template

ties back to the activities in the lab and the corresponding assessment indicators. It also contains performance criteria related to the ``format'' of the report.

You can score the lab reports using the rubric for outcome ``G'' given in Section A.4.3 and the scoring sheet provided for the experiment in that section. **Note** that each lab report scoring sheet directly corresponds to the lab report content template for that experiment. Also, note that the rubric for outcome ``G'' already contains rubrics for outcomes ``B'' and ``K'' since these outcomes appear as an integral part of the report.

To score the lab report of *one* student:

1. Print the scoring sheet for the Lab Report for the experiment they conducted in the lab. One sheet is used per student.
2. Use the ``Content'' rubric (Section A.4.3) to assign a score for each entry in the scoring sheet. The rubric gives the description of ``levels of achievement'' (4 = exemplary, 3 = proficient, 2 = developing and 1 = beginning/incomplete) for each criterion. As an example, below is a completed scoring sheet after evaluating the lab report of one student.
3. Use the ``Format'' rubric (Section A.4.3) for the ``GS-1 and GS-2'' criteria to score the formatting of the report on the same scoring sheet.

| | CONTENT | | | | | | FORMAT | |
|---|---|---|---|---|---|---|---|---|
| **Item**[1] | **K-1** | **K-2** | **B-5** | **B-6** | **B-7** | **B-9** | **GS-1** | **GS-2** |
| **I. PROCEDURE** | | | | | | | | |
| I.1. Frequency Response Experiment | | | | | | | | |
| 1 | | | 4 | | | | | |
| I.2. Bump Test Experiment | | | | | | | | |
| 1 | | | 4 | | | | | |
| I.3. Model Validation Experiment | | | | | | | | |
| 1 | | | 4 | | | | | |
| **II. RESULTS** | | | | | | | | |
| 1 | | 4 | | | | | | |
| 2 | | 3 | | | | | | |
| 3 | | 3 | | | | | | |
| 4 | | | | 3 | | | | |
| **III. ANALYSIS** | | | | | | | | |
| III.1. Frequency Response Experiment | | | | | | | | |
| 1 | | | | | 2 | | | |
| 2 | 3 | | | | | | | |
| III.2. Bump Test Experiment | | | | | | | | |
| 1 | 3 | | | | | | | |
| **IV. CONCLUSIONS** | | | | | | | | |
| 1 | | | | | | 3 | | |
| Total | 6 | 10 | 12 | 3 | 2 | 3 | 4 | 3 |

4. You can then enter the ``Total'' for each performance criterion into the assessment workbook [4] as show in Figure A.4.2.

| | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Modelling | | | | | | | | |
| | | Lab Report Content | | | | | | Report Format | | |
| | ID | K-1 | K-2 | B-5 | B-6 | B-7 | B-9 | GS-1 | GS-2 | |
| | 1 | 6 | 10 | 12 | 3 | 5 | 3 | 4 | 3 | |
| | 2 | 8 | 12 | 8 | 4 | 4 | 4 | 2 | 2 | |
| | 3 | 8 | 8 | 8 | 4 | 4 | 4 | 4 | 3 | |
| | 4 | 8 | 8 | 8 | 4 | 3 | 4 | 4 | 4 | |
| | 5 | 8 | 12 | 10 | 4 | 3 | 4 | 3 | 4 | |
| | 6 | 6 | 10 | 10 | 3 | 4 | 3 | 3 | 3 | |
| | 7 | 5 | 8 | 10 | 4 | 4 | 3 | 4 | 4 | |
| | 8 | 5 | 7 | 12 | 3 | 4 | 2 | 4 | 4 | |
| | 9 | 7 | 9 | 12 | 3 | 4 | 3 | 3 | 4 | |
| | 10 | 7 | 9 | 10 | 2 | 3 | 4 | 4 | 4 | |
| | Total Possible | 8 | 12 | 12 | 4 | 4 | 4 | 4 | 4 | |
| | *Scaled Average* | 3.40 | 3.10 | 3.33 | 3.40 | 3.80 | 3.40 | 3.50 | 3.50 | |
| | Std. Dev. | 1.23 | 1.70 | 1.63 | 0.70 | 0.63 | 0.70 | 0.71 | 0.71 | |

Figure A.4.2: Lab report score entries in the workbook for one student.

### A.4.2.4 Assessment of the outcomes for the course

As explained earlier, the performance criteria, such as A-1, A-2, A-3, are used to describe a set of measurable statements to define each learning outcome. Up to this point, we explained how to assess each performance criterion using the pre-labs, the lab reports and the scoring sheets.

A *single* score for each outcome can be computed to indicate the level of attainment of that outcome by the entire class. One approach is to simply average the scores for the performance criteria for that outcome. For example, in case of outcome ``A'', you can use:

$$SCORE_A = \frac{SCORE_{A-1} + SCORE_{A-2} + SCORE_{A-3}}{3} \tag{A.4.1}$$

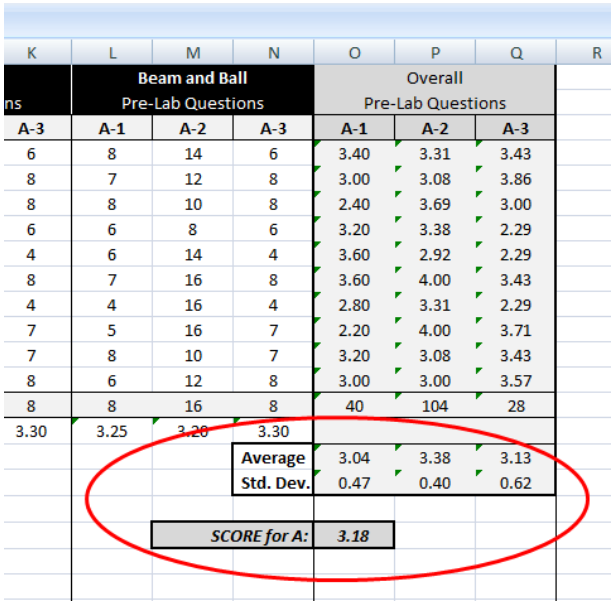
Another possibility is to use a weighted-average where some of the performance criteria are considered to be more important than the others. In case of outcome ``A'', you can use:

$$SCORE_A = \frac{w_1 \cdot SCORE_{A-1} + w_2 \cdot SCORE_{A-2} + w_3 \cdot SCORE_{A-3}}{w_1 + w_2 + w_3} \tag{A.4.2}$$

where $w_1, w_2$ and $w_3$ are weights you can assign (on the 0 to 1 scale) for the performance criteria A-1, A-2 and A-3, respectively. The total of all weights should equal 1.

### A.4.2.5 Course Score for outcome A

The assessment workbook [4] incorporates the simple average approach as shown in Figure A.4.3.



| K | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|
| ns | Beam and Ball Pre-Lab Questions | | | Overall Pre-Lab Questions | | | |
| A-3 | A-1 | A-2 | A-3 | A-1 | A-2 | A-3 | |
| 6 | 8 | 14 | 6 | 3.40 | 3.31 | 3.43 | |
| 8 | 7 | 12 | 8 | 3.00 | 3.08 | 3.86 | |
| 8 | 8 | 10 | 8 | 2.40 | 3.69 | 3.00 | |
| 6 | 6 | 8 | 6 | 3.20 | 3.38 | 2.29 | |
| 4 | 6 | 14 | 4 | 3.60 | 2.92 | 2.29 | |
| 8 | 7 | 16 | 8 | 3.60 | 4.00 | 3.43 | |
| 4 | 4 | 16 | 4 | 2.80 | 3.31 | 2.29 | |
| 7 | 5 | 16 | 7 | 2.20 | 4.00 | 3.71 | |
| 7 | 8 | 10 | 7 | 3.20 | 3.08 | 3.43 | |
| 8 | 6 | 12 | 8 | 3.00 | 3.00 | 3.57 | |
| 8 | 8 | 16 | 8 | 40 | 104 | 28 | |
| 3.30 | 3.25 | 3.20 | 3.30 | | | | |
| | | | Average | 3.04 | 3.38 | 3.13 | |
| | | | Std. Dev. | 0.47 | 0.40 | 0.62 | |
| | | SCORE for A: | | 3.18 | | | |

Figure A.4.3: Computation of single score for outcome ``A'' in the assessment workbook.

### A.4.2.6 Course Scores for outcomes B, K and G

Similarly, the simple average approach is also used for outcomes B, K and G. Referring to the rubrics in Section A.4.3, it should be noted that outcome ``G'' contains performance criteria for both ``B'' and ``K'' to assess the *content* of the report. In addition, there are two performance criteria, GS-1 and GS-2, to assess the *format* of the report. The scores for all of these performance criteria are averaged to arrive at the single score for outcome G. For example, the single score for outcome G in Figure A.4.4 for the *Modelling* experiment was calculated using:

$$SCORE_G = AVERAGE(S_{K-1} + S_{K-2} + S_{B-5} + S_{B-6} + S_{B-7} + S_{B-9} + S_{GS-1} + S_{GS-2}) \quad \text{(A.4.3)}$$

where $S_{K-1} \cdots S_{GS-2}$ are the scaled average scores for K-1 through GS-2 in the workbook.

| | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Modelling | | | | | | | | |
| | | Lab Report Content | | | | | | Report Format | | |
| | ID | K-1 | K-2 | B-5 | B-6 | B-7 | B-9 | GS-1 | GS-2 | |
| | 1 | 6 | 10 | 12 | 3 | 5 | 3 | 4 | 3 | |
| | 2 | 8 | 12 | 8 | 4 | 4 | 4 | 2 | 2 | |
| | 3 | 8 | 8 | 8 | 4 | 4 | 4 | 4 | 3 | |
| | 4 | 8 | 8 | 8 | 4 | 3 | 4 | 4 | 4 | |
| | 5 | 8 | 12 | 10 | 4 | 3 | 4 | 3 | 4 | |
| | 6 | 6 | 10 | 10 | 3 | 4 | 3 | 3 | 3 | |
| | 7 | 5 | 8 | 10 | 4 | 4 | 3 | 4 | 4 | |
| | 8 | 5 | 7 | 12 | 3 | 4 | 2 | 4 | 4 | |
| | 9 | 7 | 9 | 12 | 3 | 4 | 3 | 3 | 4 | |
| | 10 | 7 | 9 | 10 | 2 | 3 | 4 | 4 | 4 | |
| | Total Possible | 8 | 12 | 12 | 4 | 4 | 4 | 4 | 4 | |
| | *Scaled Average* | 3.40 | 3.10 | 3.33 | 3.40 | 3.80 | 3.40 | 3.50 | 3.50 | |
| | Std. Dev. | 1.23 | 1.70 | 1.63 | 0.70 | 0.63 | 0.70 | 0.71 | 0.71 | |
| | | | | | | | | | | |
| | *SCORE for K:* | *3.25* | | | | | | | | |
| | *SCORE for B:* | *3.48* | | | | | | | | |
| | *SCORE for G:* | *3.43* | | | | | | | | |

Figure A.4.4: Computation of single score for outcome ``G" in the assessment workbook.

## A.4.2.7 Assessment workbook

The *assessment workbook* [4] was developed using Microsoft Excel® . It is intented to give a general idea for how the assessment scores can be tracked and brought together. On purpose we designed the workbook to have no automatic features. You can use it as is or customize it in any way you like.

The assessment workbook has a tab for the Pre-Lab Questions and a tab for each of the laboratory chapters. Only 10 students were listed assuming you would use samples of student work and not the entire class. If you want to add more students, you can insert rows into the spreadsheets. **Note:** *If you insert new rows, make sure that the formula ranges in the cells with calculations are correct.*

At the bottom of each pre-lab section, there is a row entitled ``Total Possible". To count a pre-lab assignment in the calculation of the overall scores, you need to enter the correct totals here. For example, to count the Pre-Lab for modeling, you need to enter 12, 44 and 8 (Figure A.4.1). If you want to exclude an assignment from the overall calculation, enter ``0" as shown in Figure A.4.5. Of course, if you are excluding a pre-lab, then do not enter any scores for the students under those columns.

| K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|
| ns | Beam and Ball Pre-Lab Questions | | | Overall Pre-Lab Questions | | |
| A-3 | A-1 | A-2 | A-3 | A-1 | A-2 | A-3 |
| 6 | | | | 3.25 | 3.27 | 3.60 |
| 8 | | | | 2.88 | 3.09 | 3.80 |
| 8 | | | | 2.00 | 3.91 | 2.60 |
| 6 | | | | 3.25 | 3.64 | 2.00 |
| 4 | | | | 3.75 | 2.82 | 2.40 |
| 8 | | | | 3.63 | 4.00 | 3.20 |
| 4 | | | | 3.00 | 3.18 | 2.40 |
| 7 | | | | 2.13 | 4.00 | 3.80 |
| 7 | | | | 3.00 | 3.18 | 3.40 |
| 8 | | | | 3.00 | 3.00 | 3.40 |
| 8 | 0 | 0 | 0 | 32 | 88 | 20 |
| 3.30 | | | | | | |
| | | | Average | 2.99 | 3.41 | 3.06 |
| | | | Std. Dev. | 0.56 | 0.44 | 0.65 |
| | | | | | | |
| | | SCORE for A: | | 3.15 | | |

Figure A.4.5: Enter ``0'' to exclude or ``correct totals'' to include a Pre-Lab assignment in the calculation of the overall scores.

## A.4.3 Rubrics

| | Code | Perf. Criteria | 4<br>Exemplary | 3<br>Proficient | 2<br>Developing | 1<br>Beginning or incomplete |
|---|---|---|---|---|---|---|
| **Apply math, science and engineering** | **A-1** | Has strategies to solve the problem | Uses a sophisticated strategy. Employs refined and complex reasoning to arrive at the solution. | Uses an appropriate strategy for solution. Content knowledge is used correctly. | Has a strategy for solution but content knowledge has some conceptual errors. | Uses a wrong strategy or there is no evidence of a strategy. Content knowledge has many errors. |
| | **A-2** | Performs calculations | Arrived at correct answer. Calculations are complete. Precise math language, symbolic notation, graphs diagrams, etc. are used. | Arrived at correct answer with correct calculations. | Arrived at correct answer. Calculations are mostly correct but there are some minor errors. | No answer or arrived at wrong answer. Calculations are mostly or completely wrong. |
| | **A-3** | Explains results | Explains the result in the context of the completed calculations by providing complex reasoning and interpretations. Clear logical conclusions are drawn. | Explains the result in the context of the completed calculations. Logical conclusions are drawn. | Some explanation of the result is provided but it does not demonstrate logical reasoning. | There are no explanations of the result or an attempt was made to provide an explanation but it is incomplete or wrong. |

Table A.4.1: **OUTCOME A**: An ability to apply knowledge of mathematics, science, and engineering

| | Code | Perf. Criteria | 4<br>Exemplary | 3<br>Proficient | 2<br>Developing | 1<br>Beginning or incomplete |
|---|---|---|---|---|---|---|
| Design | **B-1** | Identifies hypothesis to test | Framed a testable question correctly and explained the anticipated cause-and-effect expectation leading to the question | Framed a testable question correctly | Framed a question that may or may not be testable | Incomplete or no testable question |
| | **B-2** | Identifies independent and dependent variables | All variables are identified correctly, explanations about their relations are provided | All variables are identified correctly | Most variables are identified correctly | None or only a few variables are identified correctly |
| | **B-3** | Lists assumptions made | All assumptions and their reasons are clearly listed | All assumptions are listed | Assumptions are listed but some are missing | No assumptions listed or most of them are missing |
| | **B-4** | Formulates experimental plan to investigate a phenomenon | Developed a sophisticated experimental procedure complete with details of every step to test the hypothesis | Developed correct experimental procedure to test the hypothesis | Attempted but could not completely develop an experimental procedure to test the hypothesis | Could not develop an accurate experimental procedure |
| Conduct | **B-5** | Follows experimental procedures | Follows experimental procedures carefully with great attention to detail. Makes precise measurements | Follows experimental procedures leading to correct measurements | Follows experimental procedures with some mistakes leading to mostly correct measurements | Follows experimental procedures with many mistakes leading to mostly wrong measurements |

(Continued on the next page)

| | Code | Perf. Criteria | 4<br>Exemplary | 3<br>Proficient | 2<br>Developing | 1<br>Beginning or incomplete |
|---|---|---|---|---|---|---|
| | **B-6** | Documents data collected | Systematically documents all data in an exemplary way and by using accurate units | Documents all data and with accurate units. | Documents data with some mistakes in the units or some data missing. Data organization needs improvement | No data are documented or there are major mistakes in the units |
| **Analyze** | **B-7** | Uses appropriate methods to analyze data | Excellent, in-depth analysis of the data using appropriate methods | Appropriate level of analysis of data using correct methods | Some data analysis but incomplete | No analysis or attempts to analyze with wrong methods |
| | **B-8** | Accounts for experimental uncertainties | Is aware of all potential experimental errors and can fully account for them with suggestions to improve them | Is aware of all potential experimental errors | Is aware of some of the potential experimental errors | Is unaware of any experimental errors |
| **Interpret** | **B-9** | Interprets results with respect to the original hypothesis | Provides clear, in-depth, accurate explanations, including trends, and arrives at logical conclusions based on data and results | Provides accurate explanations and logical conclusions based on data and results | Provides explanations and conclusions but with some errors | No explanation or conclusions are provided or they are wrong |

Table A.4.2: **OUTCOME B**: An ability to design and conduct experiments, as well as to analyze and interpret data.

| | Code | Perf. Criteria | 4<br>Exemplary | 3<br>Proficient | 2<br>Developing | 1<br>Beginning or incomplete |
|---|---|---|---|---|---|---|
| Procedure | **B-1** | Identifies hypothesis to test | Framed a testable question correctly and explained the anticipated cause-and-effect expectation leading to the question | Framed a testable question correctly | Framed a question that may or may not be testable | Incomplete or no testable question |
| | **B-2** | Identifies independent and dependent variables | All variables are identified correctly, explanations about their relations are provided | All variables are identified correctly | Most variables are identified correctly | None or only a few variables are identified correctly |
| | **B-3** | Lists assumptions made | All assumptions and their reasons are clearly listed | All assumptions are listed | Assumptions are listed but some are missing | No assumptions listed or most of them are missing |
| | **B-4** | Formulates experimental plan to investigate a phenomenon | Developed a sophisticated experimental procedure complete with details of every step to test the hypothesis | Developed correct experimental procedure to test the hypothesis | Attempted but could not completely develop an experimental procedure to test the hypothesis Could not develop an accurate experimental procedure | |
| | **B-5** | Follows experimental procedures | Follows experimental procedures carefully with great attention to detail. Makes precise measurements | Follows experimental procedures leading to correct measurements | Follows experimental procedures with some mistakes leading to mostly correct measurements | Follows experimental procedures with many mistakes leading to mostly wrong measurements |

(Continued on the next page)

| | Code | Perf. Criteria | 4<br>Exemplary | 3<br>Proficient | 2<br>Developing | 1<br>Beginning or incomplete |
|---|---|---|---|---|---|---|
| Results | **B-6** | Documents data collected | Systematically documents all data in an exemplary way and by using accurate units | Documents all data and with accurate units. | Documents data with some mistakes in the units or some data missing. Data organization needs improvement | No data are documented or there are major mistakes in the units |
| | **K-2** | Uses software tools to present data in useful format (graphs, numerical, table, charts, diagrams) | Can use various software tools and their advanced features correctly for data presentation | Can use software tools correctly for data presentation | Can use software tools for data presentation with only a few mistakes | Cannot use software tools for data presentation or attempts to use them but with many mistakes (missing labels, etc.) |
| | **K-3** | Uses software tools to simulate physical systems | Can use software tools and their advanced features correctly for simulation | Can use software tools correctly for simulation | Can use software tools for simulation with only a few mistakes | Cannot use software tools for simulation or attempts to use them but with many mistakes |
| Analysis | **B-7** | Uses appropriate methods to analyze data | Excellent, in-depth analysis of the data using appropriate methods | Appropriate level of analysis of data using correct methods | Some data analysis but incomplete | No analysis or attempts to analyze with wrong methods |
| | **B-8** | Accounts for experimental uncertainties | Is aware of all potential experimental errors and can fully account for them with suggestions to improve them | Is aware of all potential experimental errors | Is aware of some of the potential experimental errors | Is unaware of any experimental errors |
| | **K-1** | Uses software tools for analysis | Can use various software tools and their advanced features correctly for analysis | Can use software tools correctly for analysis | Can use software tools for analysis with only a few mistakes | Cannot use software tools for analysis or attempts to use them but with many mistakes |
| Conclusions | **B-9** | Interprets results with respect to the original hypothesis | Provides clear, in-depth, accurate explanations, including trends, and arrives at logical conclusions based on data and results | Provides accurate explanations and logical conclusions based on data and results | Provides explanations and conclusions but with some errors | No explanation or conclusions are provided or they are wrong |

Table A.4.3: **OUTCOME G**: Ability to communicate effectively. (for Lab Report - **CONTENT**)

| Code | Perf. Criteria | 4 Exemplary | 3 Proficient | 2 Developing | 1 Beginning or incomplete |
|---|---|---|---|---|---|
| **GS-1** | Content presentation well organized | • Each of the required sections is completed.<br>• If necessary, subsections are used<br>• All necessary background principles and information for the experiment are given<br>• All grammar/spelling correct<br>• References are cited | Two of the conditions for the "exemplary" category were not met | Three of the conditions for the "exemplary" category were not met | Four or none of the conditions for the "exemplary" category were not met |
| **GS-2** | Professional appearance | • Has cover page with all necessary details (title, course, student name(s), etc.)<br>• Typed<br>• Report layout is neat<br>• Does not exceed specified maximum page limit<br>• Pages are numbered<br>• Equations are consecutively numbered<br>• Figures are numbered, axes have labels, each figure has a descriptive caption<br>• Tables are numbered, they include labels, each table has a descriptive caption<br>• No hand drawn sketches/diagrams<br>• References are cited using correct format | Two of the conditions for the "exemplary" category were not met | Four of the conditions for the "exemplary" category were not met | Five or more of the conditions for the "exemplary" category were not met |

Table A.4.4: **OUTCOME G**: Ability to communicate effectively. (for Lab Report - **FORMAT**)

| | Code | Perf. Criteria | 4<br>Exemplary | 3<br>Proficient | 2<br>Developing | 1<br>Beginning or incomplete |
|---|---|---|---|---|---|---|
| **Use techniques, skills and modern eng. tools** | **K-1** | Uses software tools for analysis | Can use various software tools and their advanced features correctly for analysis | Can use software tools correctly for analysis | Can use software tools for analysis with only a few mistakes | Cannot use software tools for analysis or attempts to use them but with many mistakes |
| | **K-2** | Uses software tools to present data in useful format (graphs, numerical, table, charts, diagrams) | Can use various software tools and their advanced features correctly for data presentation | Can use software tools correctly for data presentation | Can use software tools for data presentation with only a few mistakes | Cannot use software tools for data presentation or attempts to use them but with many mistakes (missing labels, etc.) |
| | **K-3** | Uses software tools to simulate physical systems | Can use software tools and their advanced features correctly for simulation | Can use software tools correctly for simulation | Can use software tools for simulation with only a few mistakes | Cannot use software tools for simulation or attempts to use them but with many mistakes |

Table A.4.5: **OUTCOME K**: An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

# BIBLIOGRAPHY


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

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

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

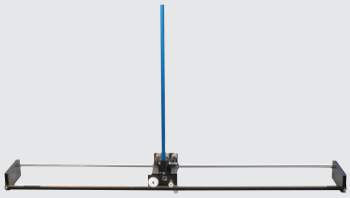
[4] Quanser Inc. *IP02 Assessment Workbook*, 2012.

[5] Quanser Inc. *Linear Servo Modeling Workbook*, 2012.

## Nine linear motion plants for teaching fundamental and advanced controls concepts

### IP02 Base Unit

### Linear Pendulum

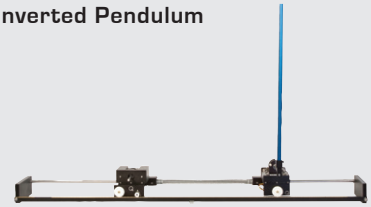


### Linear Flexible Inverted Pendulum

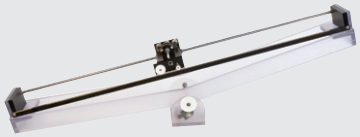
### Double Inverted Pendulum

### Linear Flexible Joint

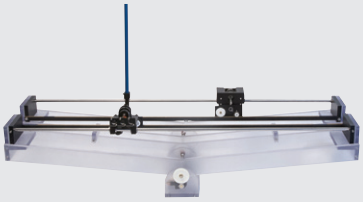
### Linear Flexible Joint with Inverted Pendulum



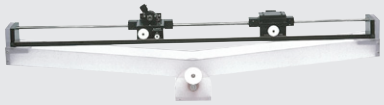
### Seesaw



### Seesaw Pendulum



### Linear Flexible Joint on Seesaw



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