Industrial Servo System

Introduction
The first part this lab is to investigate how the dynamic response of a closed-loop system can be used to determine the mass moment of inertia of a model industrial drive system in various configurations. The second part of the lab is used to study how various control systems can affect the dynamic behavior of the drive system.

Hardware

Figure 1: ECP Industrial Servo Trainer

The Industrial Servo Trainer design shown in Fig. 1 features brushless DC servo motors for both the drive motion and for disturbance generation. It also features brushless relative encoders, adjustable inertias and changeable gear ratios. It also has high resolution relative encoders, adjustable inertias and changeable gear ratios. It also introduces coulomb and viscous friction, drive train flexibility, and backlash, but these will not be used in the lab (at least, not intentionally).
The system is designed to emulate a broad range of typical servo control applications. The Model 220 apparatus consists of a drive motor (servo actuator) that is coupled via a timing belt to a drive disk with variable inertia. Another removable timing belt connects the drive disk to the speed reduction (SR) assembly while a third belt completes the drive train to the load disk. The load and drive disks have variable inertia which may be adjusted by moving (or removing) brass weights. Interchangeable belt pulleys in the SR assembly can also be used to adjust the speed reduction. The first rotating disk is coupled to the drive motor in a one-to-one ratio, so that its inertia may be thought of as being collocated with the motor. The load inertia disk, however, will rotate at a different speed than the drive motor due to the speed reduction. Also, drive flexibility and/or backlash may exist between it and the drive motor and hence its inertia is considered to be noncollocated with the motors.

A disturbance motor connects to the load disk via a 4:1 speed reduction and is used to emulate viscous friction and disturbances at the plant output. A brake below the load disk may be used to introduce Coulomb friction. Thus friction, disturbances, backlash, and flexibility may all be introduced in a controlled manner. These effects represent non-ideal conditions that are present to some degree in virtually all physically realizable electromechanical systems.

All rotating shafts of the mechanism are supported by precision ball bearings. Needle bearings in the SR assembly provide low friction backlash motion (when backlash is desired). High resolution incremental encoders couple directly to the drive ($\theta_1$) and load ($\theta_2$) disks providing position (and derived rate) feedback. The drive and disturbance motors are electrically driven by servo amplifiers and power supplies in the Controller Box. The encoders are routed through the Controller box to interface directly with the DSP board via a gate array that converts their pulse signals to numerical values.

Safety
- Before running an experiment, be sure to check that the masses have been firmly attached, and the belts are held on tight.
- Also before running a test, verify that the masses located on the Drive Inertia do not contact the Drive motor.
- When running any experiment, be sure to have the Plexiglas cover over the system and securely attached.
- After implementing a controller, first displace the disk with a light, non-sharp object (e.g. a plastic ruler) to verify stability prior to touching plant. If there is an instability or large control signal, immediately abort the control.
**Hardware/Software Equipment Check**

Please ensure that the equipment is working prior to starting the lab by following these steps:

1: With power switched off to the Control Box, enter the ECP program by double clicking on its icon. The Background Screen should appear. Gently rotate the drive or load disk by hand. Observe some following errors and changes in encoder counts. The Control Loop Status should indicate "OPEN" and the Controller Status should indicate "OK".

2: Make sure that the disks rotate freely before doing experiments. Press the black "ON" button to turn on the power to the Control Box to perform experiments. Note the green power indicator LED lit, and note the motor should remain in a disabled state until the software starts the motors moving. **Do not touch the disks** whenever power is applied to the Control Box since there is a potential for uncontrolled motion of the disks unless the controller has been safety checked.
Table 1. Test Cases For Plant Identification And Other Experiments

<table>
<thead>
<tr>
<th>Test Case</th>
<th>( n_{pd} )</th>
<th>( n_{pl} )</th>
<th>( m_{wd} ) (kg)</th>
<th>( r_{wd} ) (cm)</th>
<th>( m_{wl} ) (kg)</th>
<th>( r_{wl} ) (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>4x .500</td>
<td>5.0</td>
<td>0</td>
<td>N/A</td>
<td><strong>Drive Inertia only.</strong> Belt to SR assembly pulleys disconnected.</td>
</tr>
<tr>
<td>2</td>
<td>N/A</td>
<td>N/A</td>
<td>4x .200</td>
<td>5.0</td>
<td>0</td>
<td>N/A</td>
<td><strong>Drive Inertia only.</strong> Belt to SR assembly pulleys disconnected.</td>
</tr>
<tr>
<td>3</td>
<td>N/A</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>Same as case #1 except brass weights removed from drive inertia disk.</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>72</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>1.5:1 overall speed reduction. No brass weights on either disk.</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>72</td>
<td>4x .200</td>
<td>5.0</td>
<td>0</td>
<td>N/A</td>
<td>1.5:1 overall speed reduction. Brass weights on drive disk only.</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
<td>72</td>
<td>4x .200</td>
<td>5.0</td>
<td>4x .500</td>
<td>10.0</td>
<td>1.5:1 overall speed reduction. Brass weights on both disks</td>
</tr>
<tr>
<td>7</td>
<td>72</td>
<td>18</td>
<td>4x .200</td>
<td>5.0</td>
<td>0</td>
<td>N/A</td>
<td>24:1 overall speed reduction. Brass weights on drive disk only.</td>
</tr>
<tr>
<td>8</td>
<td>72</td>
<td>18</td>
<td>4x .200</td>
<td>5.0</td>
<td>4x .500</td>
<td>10.0</td>
<td>24:1 overall speed reduction. Brass weights on both disks</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>18</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>24:1 overall speed reduction. Brass weights on load disk only.</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>24</td>
<td>2x .200</td>
<td>5.0</td>
<td>4x .500</td>
<td>10.0</td>
<td>4.5:1 overall speed reduction. 2 brass weights on drive disk, 4 on load disk</td>
</tr>
<tr>
<td>11</td>
<td>24</td>
<td>36</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>4:1 overall speed reduction. Brass weights on load disk only.</td>
</tr>
<tr>
<td>12</td>
<td>24</td>
<td>36</td>
<td>4x .200</td>
<td>5.0</td>
<td>4x .500</td>
<td>10.0</td>
<td>4:1 overall speed reduction. Brass weights on both disks.</td>
</tr>
</tbody>
</table>
Experiment 1: System Identification

Experiment 1a: Velocity Response, Acceleration and Inertia Calculations

The following procedures will be used to obtain the velocity response of the flywheel to a step input.

Procedure:

1. Set up the hardware for the Test Case 2 listed in Table 1, where 0.2kg is the smaller weight of the two. Turn off power to the Controller box (red button) and temporarily remove the Plexiglas safety cover on the mechanism. Loosen the SR assembly clamp screw and remove the belt connecting the SR assembly to the drive inertia disk. Secure four 0.2kg weights at 5.0 cm radius on the drive disk. Verify that the masses are secured and that each is at a center distance of 5.0 cm (0.05 m) from the shaft center-line. Be certain that the Plexiglas safety cover is securely installed before proceeding.

2. Set up the ECP program to run and to acquire data. Select user units under the Set-up menu to be counts. With the controller powered up (both the Controller box and the host PC), enter the Control Algorithm box under the Set-up menu and set \( T_s = 0.002652 \text{ s} \). Enter the Command menu, go to Trajectory, deselect Unidirectional moves (i.e. enabling bidirectional inputs), and select Step input. Select Open Loop Step and input a step size of 2.0 volts, a duration of 200 ms and 2 repetitions. Go to Set up Data Acquisition in the Data menu and select encoder 1 as data to acquire and specify data sampling every one servo cycle (i.e. every one \( T_s \)'s). Select OK to exit. This sets up the system to accelerate the drive disk with 2.0 V input to the servo amplifier for 200 ms forward, then 200 ms with zero input, and then 2.0 V input 200 ms backward while acquiring Encoder 1 position data every 13 ms.

3a. Reset the encoder positions to zero using the Utility menu. Select Execute from the Command menu and select Run. The drive disk will accelerate forward, dwell at constant velocity, then return. Encoder 1 data is collected to record the response.

3b. Plot on the screen to see encoder 1 velocity vs. time. There should be an approximately linear positive and negative slopes separated by approximately constant velocity.

3c. Export the data to save in a file using ‘export raw data’ in the data menu. Use the matlab program, plotdata.m, on the class website to plot Encoder 1 velocity vs. time (plot key iplot=-1). Adjust the ‘istep’ number in the program so that the slope in the plot looks reasonably smooth. Note that the angular velocity is in counts/s, which needs to be converted to rad/s later in your angular acceleration calculations.

4a. Use Data Curser tool in the matlab to measure the time difference and the velocity difference through the linear section of the run-up part of the curve. Obtain the acceleration (counts/s^2) by calculating the slope of the run-up
portion of the measured $\dot{\theta}(t)$ data. Convert the angular acceleration $\ddot{\theta}(t)$ to rad/sec$^2$, given that 1 revolution = 16000 counts.

4b. Repeat the procedure in 4a to the run-down part of the curve to determine another value of $\ddot{\theta}(t)$. **Common on how close it is to that determined in 4a.**

5. Using the equation, $T = J_{dw} \ddot{\theta}$ and $\ddot{\theta}$ from 4a, solve for the mass moment of inertia, $J_{dw}$, for the tested system in unit of N-s$^2$/m. The amplifier converts the voltage command to current using a ratio, $k_a$, of:
   $$k_a = 2.34 \text{ amps/volts}$$
   and the motor converts current into torque, $T$, using a ratio, $k_t$, of:
   $$k_t = 0.1 \text{ N-m/amp}$$

6. Use the parallel axis theorem to determine the drive disk inertia, $J_{dd}$, without the 4 weights.

**The report of this part is expected to include:**

One matlab plot, along with title, labels and data cursor points used in your calculations
  - Plot of Encoder 1 angular velocity vs. time

Calculations or clear explanations on how the following values were determined, along with units for each value:
  - Angular acceleration in counts/sec$^2$ (for both 4a and 4b, noting difference)
  - Angular acceleration, $\ddot{\theta}$, in rad/sec$^2$ using 4a data.
  - Mass moment of inertia, $J$, in N-s$^2$/m
  - Mass moment of inertia, $J_{dd}$, excluding the four weights

**Experiment 1b: Inertia Calculation via Closed-Loop System Response**

In this section, the inertia, gain, and damping of the various system components are found indirectly by measuring their effect on system response characteristics. In these tests, we will close a proportional plus rate feedback loop about the drive feedback encoder (Encoder 1). The corresponding block diagram is shown in Figure 2 below:

**Figure 2. Controller Configuration for Plant Identification**
The output/input transfer function of the system is given by

\[ c(s) = \frac{\theta_1(s)}{r(s)} = \frac{k_pkhw/J}{s^2 + (c + k_dkhw/J)s + k_pkhw/J} \]  \hspace{1cm} (Equation 1-1)

which has the form of the classical second order system:

\[ c(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  \hspace{1cm} (Equation 1-2)

where

\[ \omega_n \triangleq \sqrt{\frac{k_pkhw}{J}} \]  \hspace{1cm} (Equation 1-3)

is called the system natural frequency, and

\[ \zeta \triangleq \frac{1}{2\omega_n} \left( \frac{c + k_dkhw}{J} \right) \]  \hspace{1cm} (Equation 1-4)

is the system damping ratio. When the plant frictional damping is negligible compared to that supplied by \( k_d \), the damping ratio reduces to:

\[ \zeta \approx \frac{k_dkhw}{2J\omega_n} = \frac{k_dkhw}{2\sqrt{Jk_pkhw}} \]  \hspace{1cm} (Equation 1-5)

The system hardware gain, \( k_{hw} \), is comprised of:

\[ k_{hw} = k_ck_dk_ck_s \]  \hspace{1cm} (Equation 1-6)

where:

- \( k_c \), the DAC gain, = 10V / 32,768 DAC counts
- \( k_a \), the Servo Amp gain, = 2.34 (amp/V)
- \( k_t \), the Servo Motor Torque constant = 0.1 (N-m/amp)
- \( k_e \), the Encoder gain, = 16,000 counts/2\pi radians
- \( k_s \), the Controller Software gain, = 32 (controller input counts/encoder counts)

Hence, \( k_{hw} \) has the dimensions of torque but is more precisely expressed in units of \([{(N\cdot m)} / {rad}) \ast (controller \ input \ count) / (DAC \ count)]\). Calculate \( k_{hw} \) for later use.

In the model above, \( J \) is the system inertia reflected to the encoder output location.
**Measurement Procedure for Experiment 1b**

In this procedure, a frequency measurement technique is utilized to determine again the previously calculated drive disk inertia, $J_{dd}$. **Comparisons are to be made between the two methods of determinations.**

**Procedure:**

1. Set up the hardware for the test. Turn off power to the Controller box. Place the mechanism in the Test Case 3 configuration in Table 1. Be certain that the plexiglass safety cover is securely installed before proceeding.

2. Set up the controller. With the controller powered up, enter the Control Algorithm box under the Set-up menu and set $T_s=0.002652$ s and select Continuous Time Control. Select PI With Velocity Feedback and Set-up Algorithm. Enter $k_p = 0.5$ and $k_d = 0.001$ ($k_i = 0$) and select OK.

In this and all future work, be sure to stay clear of the mechanism before doing the next step. Select Implement Algorithm to implement the specified controller. Displace the disk with a light, non sharp object to verify system stability.

3. Configure the input to the system. Enter the Command menu, go to Trajectory and select Step input. Select Closed Loop Step and input a step size of 1000 counts, a duration of 1000 ms and 1 repetition. Exit by consecutively selecting OK. This puts the controller board in a mode for performing a pair of closed loop step-inputs (one forward then one backward) of one second duration. This procedure may be repeated and the duration adjusted to vary the maneuver and data acquisition period.

4. Set up the data acquisition parameters. Go to Set up Data Acquisition in the Data menu and select encoder 1 Position as data to acquire and specify data sampling every 1 (one) servo cycles. Select OK to exit. Select Zero Position from the Utility menu to zero the encoder positions.

5. Run the test and record data. Select Execute from the Command menu and select Run. The drive disk will step, oscillate, and attenuate, then return. Encoder data is collected to record this response.

6. Export the data to matlab. Plot the Encoder 1 vs time with plot key iplot=1.

7. Determine system damping ratio, $\zeta$. Use Data Curser to determine the amplitude and time to peak of the first one or two consecutive cycles. Measure the reduction from the initial cycle amplitude $X_0$ to the last cycle amplitude $X_n$ for the $n$ cycles.

The following relationship is associated with the **logarithmic decrement** for underdamped second order systems:

\[
\frac{\zeta}{\sqrt{1-\zeta^2}} = \frac{1}{2\pi n} \ln \left( \frac{X_0}{X_n} \right)
\]  

(Equation 1-9)

For small $\zeta$ this expression simplifies to:
8. Determine system natural frequency, $\omega_n$. Divide the number of cycles by the time taken to complete them to determine the frequency of oscillation, $\omega_d$, in Hz. Convert it to rad/sec. This *damped frequency*, $\omega_d$, is related to the *natural frequency*, $\omega_n$, according to:

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}}$$  \hspace{1cm} \text{(Equation 1-11)}

where

$$\zeta = \frac{1}{2\pi n} \ln \left( \frac{X_0}{X_n} \right)$$  \hspace{1cm} \text{(Equation 1-10)}

9. Determine drive disk inertia, $J_{dd}$. The inertia can be determined using Eq. 1-3. Compare it to $J_{dd}$ determined in Experiment 1a. Comment their difference between the two calculations, which is expect to be small.

The report for this part is expected to include:

One plot along with title, labels and data cursor points used to calculate the damping ratio and natural frequency of the system.
- Plot of Encoder 1 position vs. time for Test Case 3

Include the calculations above along with explanations as needed. Clearly report the following calculated values:
- Hardware gain, $k_{hw}$, from Eq. 1-6
- Damping ratio from Equation 1-10
- Natural frequency from Eq. 1-11
- Drive disk inertia from Eq. 1-3. Compare it to $J_{dd}$ determined in Experiment 1a and comment on the comparison.

**Experiment 1c: Inertia Calculations with Load Disk and Weights**

Now connect the load disk and inertias to the previous stage using a connecting pulley. Set up the system as shown in Test Case 6 in Table 1. Make certain that the belt pulleys are properly tightened. Repeat Steps 1 through 8 above for this new condition to determine the inertia of this modified system. The trajectory duration in Step 3 may need to be increased to *3000 ms* or longer to satisfactorily view the lower frequency motion. The step size may also need to be doubled to *2000 counts* to generate sufficient response amplitude. (It is recommended to explore these control increases in a couple of trials starting with the values used previously.)

1. Plot the data in matlab. Calculate damping ratio, $\zeta_6$, natural frequency, $\omega_{n6}$, and system inertia, $J_6$, similar to what you did in Experiment 1b.

2. Repeat the experiment with the four 0.5kg weights removed from the load disk, which is Test Case 5 in Table 1. Generate the response plot and perform the calculation of Step 1 above to obtain $\zeta_5$, $\omega_{n5}$ and $J_5$.  

3. Determine the inertia of the four 0.5kg weights, \( J_{wl} \), with respect to the center of the load disk using parallel axis theorem. This inertia reflected to the drive disk is equal to \( J_{wl}R^2 \), where \( R \) is the ratio of the load-disk speed to the drive-disk speed. Determine \( R \) from your calculations of \( J_6 \), \( J_5 \), and \( J_{wl} \), where \( J_6 \) and \( J_5 \) are the system inertias for Test Cases 6 and 5 with respect to the drive disk.

The report in this part is expected to include:

Two matlab plots along with titles, labels and data cursor points used to calculate the frequency of the system.
- Plot of Encoder 1 position vs. time for Test Case 6
- Plot of Encoder 1 position vs. time for Test Case 5
- Determination of the ratio of the load-disk speed to the drive-disk speed

Include the calculations in all three steps along with explanations as needed.
### Experiment 2: Rigid Body PD & PID Control

This experiment demonstrates some key concepts associated with proportional plus derivative (PD) control and subsequently the effects of adding integral action (PID). This control scheme, acting on plants modeled as rigid bodies finds broader application in industry than any other. It is employed in such diverse areas as machine tools, automobiles (cruise control), and spacecraft (attitude and gimbal control). The block diagram for velocity feedback PID control of a rigid body is shown in Figure 6.2-1\(^1\) where friction is neglected. The closed loop transfer function is:

\[
C(s) = \frac{\theta(s)}{r(s)} = \frac{(k_{hw}/J)(k_p s + k_i)}{s^3 + (k_{hw}/J)(k_ds^2 + k_p s + k_i)} \quad \text{(Equation 2-1)}
\]

![Figure 6.2-1. Rigid Body PID Control – Control Block Diagram](image)

For the first portion of this exercise we shall consider PD control only \((k_i = 0)\) which reduces the closed loop system to:

\[
C(s) = \frac{\theta(s)}{r(s)} = \frac{(k_{hw}/J)(ks + k_p)}{s^2 + (k_{hw}/J)(k_ds + k_p)} \quad \text{(Equation 2-2)}
\]

\(^1\)Another common form of PID control in which the derivative term is in the forward path is shown below with its transfer function:

\[
C(s) = \frac{\theta(s)}{r(s)} = \frac{(k_{hw}/J)(k_ds^2 + k_p s^2 + k_i)}{s^3 + (k_{hw}/J)(k_ds^2 + k_p s + k_i)}
\]

This form has generally better tracking performance but can lead to high instantaneous control effort. It is studied in Part 3 of the lab.
As before, we define:

\[ \omega_n = \Delta \sqrt{\frac{k_p k_w}{J}} \]  \hspace{1cm} (Equation 2-3)

\[ \zeta = \frac{k_d k_w}{2J \omega_m} - \frac{k_d k_w}{2\sqrt{J k_p k_w}} \]  \hspace{1cm} (Equation 2-4)

so that we may express:

\[ c(s) = \frac{\omega_n^2}{s^2 + 2\zeta \omega_m s + \omega_n^2} \]  \hspace{1cm} (Equation 2-5)

The effect of \( k_p \) and \( k_d \) on the roots of the denominator (damped second order oscillator) of Eq (2-2) are considered in the work that follows.

**Experimental Testing**

This experiment will demonstrate some of the more silent concepts of PD and PID control. Follow the procedures below to study the effects of \( k_p \) and \( k_d \).

**Experiment 2a: Proportional (P) Control**

1. Set-up the apparatus in Test Case 2 configuration so that the value of the inertia, \( J \), in the above equations is what you determined in Experiment 1a.
2. Verify that the plexiglass safety cover is in place and the brass weights are securely fastened.
3. From Eq (2-3) determine the value of \( k_p \) (\( k_d = 0 \)) so that the system behaves like a 2 Hz or \( \omega_n = 4\pi \) rad/s spring-inertia oscillator.
4. Configure the data acquisition. Set-up to collect Encoder 1 data via the Set-up Data Acquisition box in the Data menu. Set up a closed-loop step of 0 (zero) counts, dwell time = 3000 ms, and 1 (one) rep (Trajectory in the Command menu). This puts the controller board in a mode for acquiring 6 sec of data on command while the control system will maintain regulation (\( r(s) = 0 \)). This procedure may be repeated and the duration adjusted to vary the data acquisition period.
5. Configure the controller. Enter the Control Algorithm box under Set-up and set \( Ts=0.000884 \) s and select Continuous Time Control. Select PI with Velocity Feedback and Set-up Algorithm. Enter the \( k_p \) value determined above for \( \omega_n = 4\pi \) rad/s oscillation (\( k_d \) & \( k_i \) = 0) and select OK.

**Stay clear of the mechanism and select Implement Algorithm.**
6. Enter Execute under Command. Manually rotate the drive disk roughly 60 deg and hold. Release the disk and click run immediately after to record data. Do
not hold the rotated disk for too long as it may cause the motor drive thermal protection to open the control loop.

7a. Plot encoder 1 output vs. time on screen and then in matlab. Use Data Curser to determine the frequency of oscillation. *If the calculated $k_p$ does not give you a response with roughly 2 cycles per second, check your calculations. If you can’t find calculation error, talk to TA or experimentally determine a $k_p$ which does.*

7b. Repeat Steps 5 & 6 with twice a $k_p$ value and plot the response. *(Do not input value greater than $k_p = 0.2$). What is the effect of doubling $k_p$?*

**Experiment 2b: Derivative (D) Control**

8. Determine the value of the derivative gain, $k_d$, to achieve $k_d k_h w = 0.05$ N-m/(rad/s). Do not input value greater than $k_d = 0.05$. Set a larger sampling period of $T_s=0.006188$ s to reduce noise from numerical integration. Input the above value for $k_d$ and set $k_p$ & $k_i = 0$. Repeat Step 5

9. After checking the system for stability by displacing it with a ruler, manually move the disk back and forth to feel the effect of viscous damping provided by $k_d$.

10. Repeat Steps 8 & 9 for a value of $k_d$ five times as large *(Again, $k_d \leq 0.05$).* Can the effects of increased damping be felt?

**The report of this part is expected to include:**

- Calculated $k_d$ with the equation.

For all the questions **highlighted**, the questions should be copied and pasted into the report and answered immediately thereafter.
Experiment 2c: Proportional and Derivative (PD) Control

Follow the procedures below to create and implement the PD controller (k_i = 0). Include all of the requested plots with this report.

1. From Eq's 2-3 and 2-4, design the controllers (i.e. determine k_p and k_d) for a system natural frequency of \( \omega_n = 4\pi \text{ rad/s} \), and three damping cases: 1) \( \zeta = 0.2 \) (under-damped), 2) \( \zeta = 1.0 \) (critically damped), 3) \( \zeta = 2.0 \) (over-damped).

2. Implement the underdamped controller with \( T_s = 0.00442 \text{ s} \). Set up a trajectory for a 2000 count closed-loop Step with 3000 ms dwell time and 1 rep.

3. Set up Data Acquisition in the Data menu and select commanded position and Encoder 1 as data to acquire. Execute this trajectory. Plot on screen both the command and response on the same vertical axis so that there is no graphical bias. Export the data in a file and plot the results in matlab (iplot=2). Use Data Curser to help determine the natural frequency and damping ratio, making sure it is reasonably close to what you designed for.

4. Repeat Steps 2 & 3 for the critically damped and over-damped cases. Look at results on screen to see if they are indeed largely damped.

5. Export the data for both cases to your matlab folder. Then plot all three cases in one figure using program plotdata3.m. Do the responses agree with that expected for a damped second order system? How does the response compare with that of a classical spring/mass/damper system having the natural frequency and damping ratios specified in Step 1?

The report of this part is expected to include:

Two matlab plots along with titles and labels:
- Plot for the underdamped case
- Plot for all three cases

Clearly report the following values and their calculations:
- Value of k_p to give a frequency of \( \omega_n = 4\pi \text{ rad/s} \)
- Underdamped value of k_d
- Critically damped value of k_d
- Overdamped value of k_d
- Percentage of the steady-state error for each of the three cases (ie. difference between the step input and the response at the end of response transition).

For all the questions highlighted, the questions should be copied and pasted into the report and answered immediately thereafter.
**Experiment 2d: Proportional, Integral and Derivate (PID) Control**

Follow the procedures below to create and implement the PID controller

1. Compute $k_i$ such that $k_i/k_{hw} = 1.0 \text{ N-m/(rad-sec)}$. Implement a controller with this value of $k_i$ and the critically damped $k_p$ & $k_d$ parameters from Step 1 of the previous part. (Do not input $k_i > 2.2$). Execute a 2500 count closed-loop step of 2000 ms duration with 1 rep. Plot the encoder 1 response and commanded position to one vertical axis.

2. Increase $k_i$ by a factor of two, implement the controller and plot its step response. **Compare it with the response obtained in Step 1 and note the key differences.**

3. Compare the plot obtained in Step 2 to that obtained in Experiment 2c for the critically damped case with $k_i = 0$. **What are the integral action's effects on the steady state error? How does the integral action affect overshoot?**

The report of this part is expected to include:

Three plots along with titles, labels and a legend to distinguish the data.
- Plot of input and response for $k_i = 0$
- Plot of input and response for $k_i$ determined in Step 1
- Plot of input and response for $2k_i$

Nice to put all plots in one page of the report for easy comparisons.

For all the questions **highlighted**, the questions should be copied and pasted into the report and answered immediately thereafter.
Experiment 3: Velocity Feedforward PID Control System

The control system studied in Experiment 2 is for a velocity feedback configuration. This part of the lab explores the effects of velocity feedforward PID control. The block diagram of this control is shown in the second diagram on Page 11.

1. Set up the mechanism as in the previous sections (Test Case 2). Set \( T_s = 0.00442 \text{ s} \) and implement a velocity feedback controller with \( k_i = 0 \). Set \( k_p \) and \( k_d \) for \( \omega_n = 4\pi \text{ rad/s} \) and critical damping as was done in Experiment 2. Set up Data Acquisition to collect data every 2 servo cycles.

2. Set up a closed loop ramp trajectory with Distance = 8000 counts, Velocity = 20,000 counts/sec, and Dwell Time = 400 ms. Execute this maneuver, collect data and plot Commanded Position and Encoder 1 Position.

3. Repeat steps 1 and 2 using forward path PID control (PID, under Setup Control Algorithm), first with \( k_i = 0 \), then with a \( k_i \) to give \( k_i k_{hv} = 3 \text{ N-m/(rad-s)} \). Can you hear the difference in the drive (due to peak control effort) between the responses with forward path and return path differentiators?

Briefly describe the differences observed between using \( k_d \) in the forward and return paths. Does either case overshoot? What was the effect of adding integral action with \( k_d \) in the forward and return paths?

The report of this part is expected to include:

Three plots along with titles, labels and a legend to distinguish the data
- A plot of ramp response with velocity feedback control and \( k_i = 0 \).
- A plot of ramp response with velocity feedforward control and \( k_i = 0 \).
- A plot of ramp response with velocity feedforward control and the non-zero \( k_i \).

Nice to put all plots in one page of the report for easy comparisons.

State the values of control parameters in each case along with the equations used in the calculations. For all the questions highlighted, the questions should be copied and pasted into the report and answered immediately thereafter.