ELECENG 3CL4: Introduction to Control Systems
Lab 3: Proportional Control & Proportional with Velocity Feedback Control of DC Motor Servomechanism

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Objective

To design a proportional controller and a proportional controller with velocity feedback for the DC motor servomechanism, and explore trade-offs involved in the selection of the controller parameters and their impact on transient and steady-state responses of the control system.

Assessment

This laboratory is conducted in groups of no more than two students. Students are required to attend their assigned lab section. The assessment of this lab will occur based on your answer to the pre-lab questions, in-lab activities, and a written laboratory report. **Each group is required to submit their answers to the pre-lab questions as a hard copy at the beginning of their designated lab session to the Teaching Assistants (TAs) on duty.** No marks will be awarded to pre-labs submitted 10 minutes after the designated start time of the lab session. Only one submission is necessary per group. **Both group members should clearly state their full names, student numbers, Lab section, and Class section(s) on the title page of the pre-lab answers document.** It is up to you if you want to submit a handwritten document or a printed one. You will earn a maximum of 100 marks from Lab 3 activities. **Lab 3 will constitute 5% of your total grade for this course**. The components of the assessment are as follows:

- Pre-lab Questions (40 marks), which must be completed before the lab and submitted at the beginning of the lab. **This Lab Manual contains 14 Pre-Lab questions.** See Sections 1 to 3.
- Three experiments (35 marks). See Sections 4 to 6.
- A laboratory report (25 marks). See Section 7.

Your performance in the experiments will be evaluated during the lab by the TA's. The marks for each component are clearly indicated in this lab manual.

1 Proportional Control of DC Motor

Recall from Lab 2 that the operation of the DC servomotor that we are considering can be approximated by the second-order transfer function

$$G(s) = \frac{A}{s(s\tau_m + 1)}. \tag{1}$$

where A is a *gain* parameter while τ_m is the motor's *time constant*. Now, consider the closed-loop control system in Fig. 1, with the motor as the process, $H(s) = 1$, and the proportional controller $G_c(s) = K_p$.

We would like to acknowledge the efforts of Dr. Ayman Negm in the development of this lab.

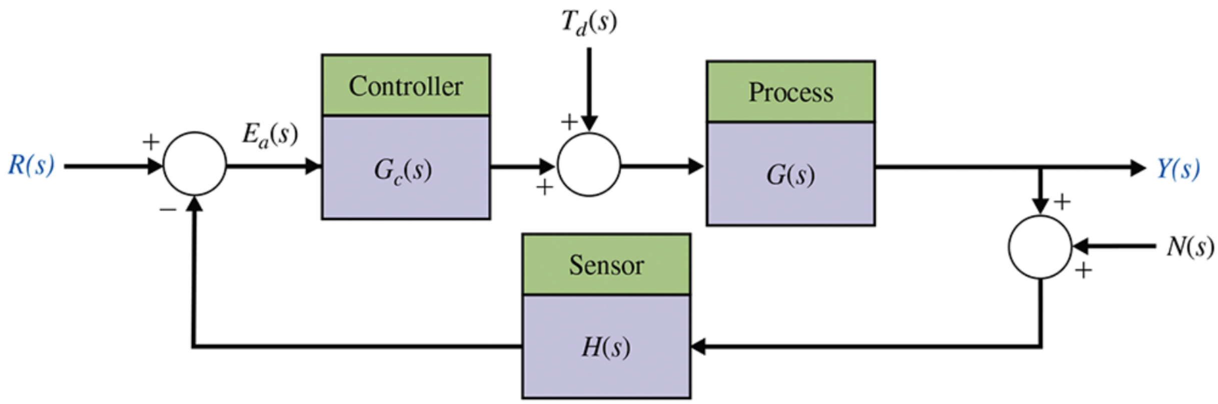

Figure 1: Feedback system with $Y(s) = \Theta(s)$. We will consider the case in which $H(s) = 1$. The disturbance signal $T_d(s)$ is used to model friction torque in the motor, but it could also model any additional external torque applied to the shaft. We will neglect the measurement noise signal $N(s)$. (Figure 4.4 of Dorf and Bishop, *Modern Control Systems*, 14th edition, Pearson, 2022). Note: This figure is in the Laplace domain.

Pre-Lab Question 1 **(2 marks)** *Provide a complete derivation of the following expression for the closed-loop poles [Hint: The first step is to find the closed-loop transfer function from $R(s)$ to $Y(s)$ in Figure 1, when $H(s) = 1$, $N(s) = 0$, and $T_d(s) = 0$]:*

$$p_{1,2} = -\frac{1}{2\tau_m} \pm \frac{1}{2\tau_m}\sqrt{1 - 4K_pA\tau_m} \tag{2}$$

Pre-Lab Question 2 **(4 marks)** *Rewrite the closed loop transfer function in the form of a standard second order system and show that:*

$$\zeta\omega_n = \frac{1}{2\tau_m}, \quad \omega_n = \sqrt{\frac{K_pA}{\tau_m}}, \quad \zeta = \frac{1}{2\sqrt{K_pA\tau_m}} \tag{3}$$

where ζ is the damping ratio and ω_n is the natural frequency.

Pre-Lab Question 3 **(1 mark)** *Show a controller gain that would yield a critically damped closed loop is given by*

$$K_p = \frac{1}{4A\tau_m} \tag{4}$$

Pre-Lab Question 4 **(2 marks)** *Show that if $K_p > \frac{1}{4A\tau_m}$, then the pole positions can be written as*

$$p_{1,2} = \frac{1}{2\tau_m}\big(-1 \pm j\tan(\phi)\big) \tag{5}$$

with $\phi = \cos^{-1}(\zeta)$. Note that in this lab we will use ϕ to denote the damping angle (with the negative real axis), because we have already used θ for the angle of the motor.

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2 Trade-offs in Proportional Control of a Servomotor: Theoretical Insight

Recall that the closed loop transfer function of the system in Fig. 1 with $H(s) = 1$, $G_c(s) = K_p$, $T_d(s) = 0$, $N(s) = 0$, and the motor as the process is:

$$T(s) = \frac{\Theta(s)}{R(s)} = \frac{K_p G(s)}{1 + K_p G(s)} \tag{6a}$$

$$= \frac{K_p A}{s(s\tau_m + 1) + K_p A} \tag{6b}$$

$$= \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{6c}$$

where $\omega_n = \sqrt{\frac{K_p A}{\tau_m}}$ and $\zeta = \frac{1}{2\omega_n \tau_m}$. When $K_p > \frac{1}{4A\tau_m}$, the system is underdamped, and servomechanisms are often operated in this mode. When $K_p > \frac{1}{4A\tau_m}$, the step response of the system is

$$\theta(t) = 1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin\left(\omega_n \sqrt{1-\zeta^2}\, t + \phi\right) \tag{7}$$

where $\cos(\phi) = \zeta$. A typical step response is shown in Fig. 2.

When we design a simple proportional controller for this type of servo mechanism, we often consider the following transient response performance criteria:

1. The 2% settling time, T_s (discussed in class);
2. The percentage overshoot, P.O. (discussed in class);
3. The 10% to 90% rise time, T_{r1} (not discussed in class, however, defined below).

Definition: The ***Rise Time*** is a measure of the swiftness of the step response and is the time it takes for the response to rise to the height of the step input for the first time. It is marked as T_r in Fig. 2. A modified version is the **10% to 90% *Rise Time***, which as the name implies, is the time it takes for the response to rise from 10% to 90% of the magnitude of the step input. It is marked as T_{r1} in Fig. 2. Thus, for example, if the height of the step input is 2 radians then T_{r1} will be the time it takes for the step response to go from 0.2 to 1.8 radians. While it is difficult to obtain an exact analytic expression for T_{r1}, the linear approximation given in Eq. (10) is reasonably accurate for $0.3 \le \zeta \le 0.8$.

Typically, we would like to design K_p so as to have the settling time, the percentage overshoot and the rise time to all be small. The purpose of this section is to assess the extent to which this can be achieved.[1]

To begin the design process, we would like to determine the relationship between the three design quantities of interest and our design parameter, the gain K_p. To do so, recall from lectures that for a generic second-order under-damped system with a transfer function of the form in (6c), the 2% settling time is approximately four time constants. That is,

$$T_s \approx \frac{4}{\zeta\omega_n}. \tag{8}$$

[1] If there are fundamental restrictions on this goal that cannot be overcome, then we need to consider more sophisticated controllers, such as those that involve integration and differentiation of the error signal, as well as just amplification.

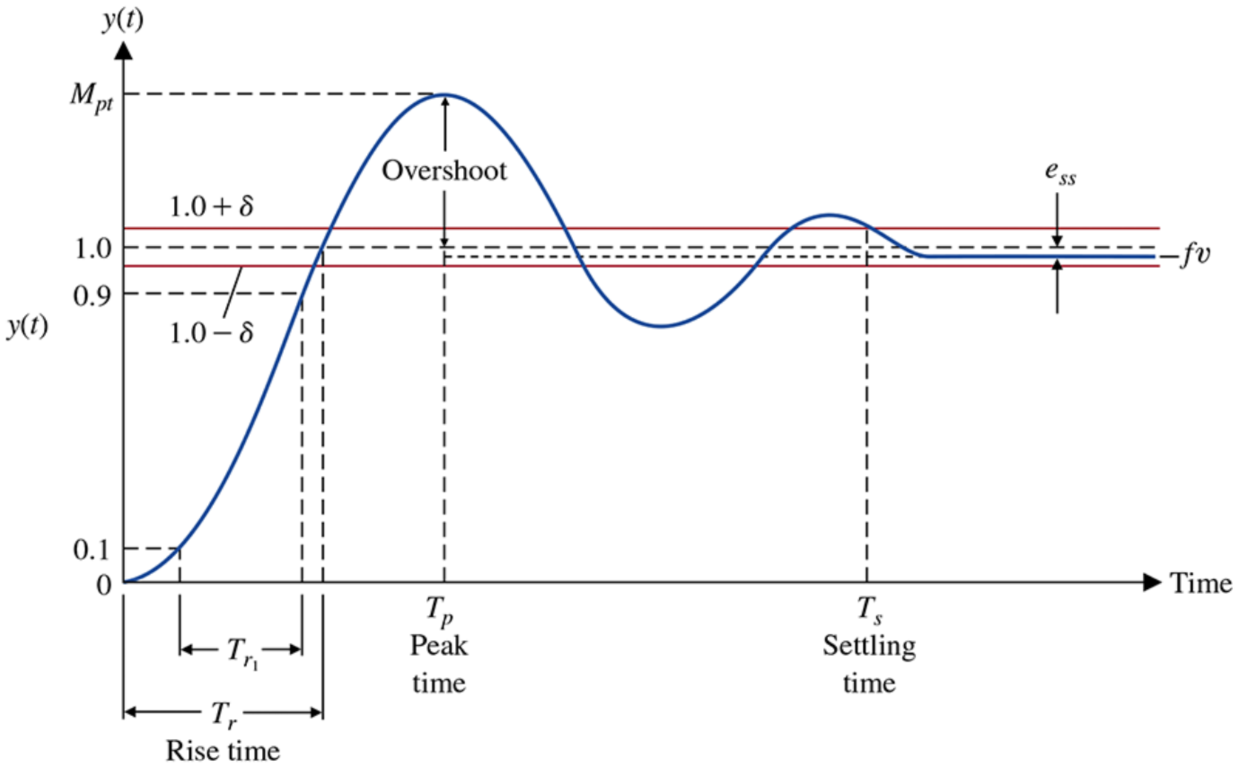

Figure 2: Generic step response of an under-damped second-order system (Figure 5.6 of Dorf and Bishop, *Modern Control Systems*, 14th edition, Pearson, 2022).

Also recall from lectures that for an under-damped system, for which $0 < \zeta < 1$, the percentage overshoot is

$$\text{P.O.} = 100 \exp\left(-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}\right), \tag{9}$$

And for moderately underdamped systems for which $0.3 \leq \zeta \leq 0.8$, the 10%–90% rise time can be approximated by

$$T_{r1} \approx \frac{2.16\zeta + 0.6}{\omega_n}. \tag{10}$$

Pre-Lab Question 5 (3 marks) *Use the above expressions to show that for the closed loop system in Fig. 1 with* $K_p > \frac{1}{4A\tau_m}$

$$T_s \approx 8\tau_m \tag{11}$$

$$\text{P.O.} = 100 \exp\left(-\frac{\pi}{\sqrt{4K_pA\tau_m - 1}}\right) \tag{12}$$

$$T_{r1} \approx \frac{2.16 + 1.2\sqrt{K_pA\tau_m}}{2K_pA}. \tag{13}$$

Pre-Lab Question 6 (2 marks) *How do these terms change with increasing* K_p*?*

Pre-Lab Question 7 (2 marks) *What are the implications for design?*

In addition to the transient response characteristics considered above, we are often interested in the steady-state response of the system to a step reference input $R(s) = \frac{\theta_d}{s}$ and constant (step) disturbance input $T_d(s) = \frac{\tau_d}{s}$; the disturbance input can be used to model friction in the motor. Thus, in the questions that follow, in addition to a step input $R(s)$, we will also consider a step disturbance $T_d(s)$.

Pre-Lab Question 8 (3 marks) *Show that the total output response to the reference and disturbance inputs in the Laplace domain is given by:*

$$Y(s) = \frac{\frac{K_p A}{\tau_m}}{s^2 + \frac{1}{\tau_m}s + \frac{K_p A}{\tau_m}} R(s) + \frac{\frac{A}{\tau_m}}{s^2 + \frac{1}{\tau_m}s + \frac{K_p A}{\tau_m}} T_d(s) \tag{14}$$

Pre-Lab Question 9 (2 marks) *What is the steady-state error in response to a step input $R(s) = \frac{\theta_d}{s}$ in the absence of disturbance, i.e, when $T_d(s) = 0$.*

Pre-Lab Question 10 (3 marks) *What is the steady-state error in response to a step input $R(s) = \frac{\theta_d}{s}$ in the presence of a constant (step) disturbance, i.e, $T_d(s) = \frac{\tau_d}{s}$? What is the impact of the proportional controller's gain K_p on this error?*

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3 Proportional Controller with Velocity Feedback

The theoretical and experimental developments with the proportional controller in the previous sections revealed limitations of this controller for the servo-mechanism. The choice of only one design parameter K_p leads to a trade-off between competing design objectives of fast rise time, small error in response to a constant disturbance, and a small overshoot in the step response. Furthermore, the settling time is unaffected by the controller gain. To help alleviate these shortcomings in the proportional control of the servo-mechanism (DC motor), a velocity feedback loop is added to the system as shown in Figure 3. Unlike in a conventional *Proportional-Derivative* (PD) controller where the differentiator acts on the error $e(t) = r(t) - y(t)$, the derivative is only applied to $y(t)$ as can be seen in Figure 3. In the case of a step reference $r(t)$, this modified controller arrangement avoids generating an unbounded control signal due to $\dot{r}(0)$ being unbounded. It can be noted from Figure 3 that the velocity feedback path has a gain K_v which determines the contribution of velocity feedback. Thus, now we have two design parameters, K_p and K_v. In the pre-lab questions that follow, we will investigate whether having these two design parameters can aid us in achieving multiple design objectives simultaneously.

Pre-Lab Question 11 (5 marks) *Using the block diagram in Figure 3, show that the total output response to the reference and disturbance inputs is given by:*

$$Y(s) = \frac{\frac{K_p A}{\tau_m}}{s^2 + \frac{1+K_v A}{\tau_m}s + \frac{K_p A}{\tau_m}} R(s) + \frac{\frac{A}{\tau_m}}{s^2 + \frac{1+K_v A}{\tau_m}s + \frac{K_p A}{\tau_m}} T_d(s) \tag{15}$$

Pre-Lab Question 12 (2 marks) *Show that the magnitude of steady-state error due to a step input $R(s) = \frac{\theta_d}{s}$ and a step disturbance $T_d(s) = \frac{\tau_d}{s}$ is given by:*

$$|e_{ss}| = \frac{\tau_d}{K_p} \tag{16}$$

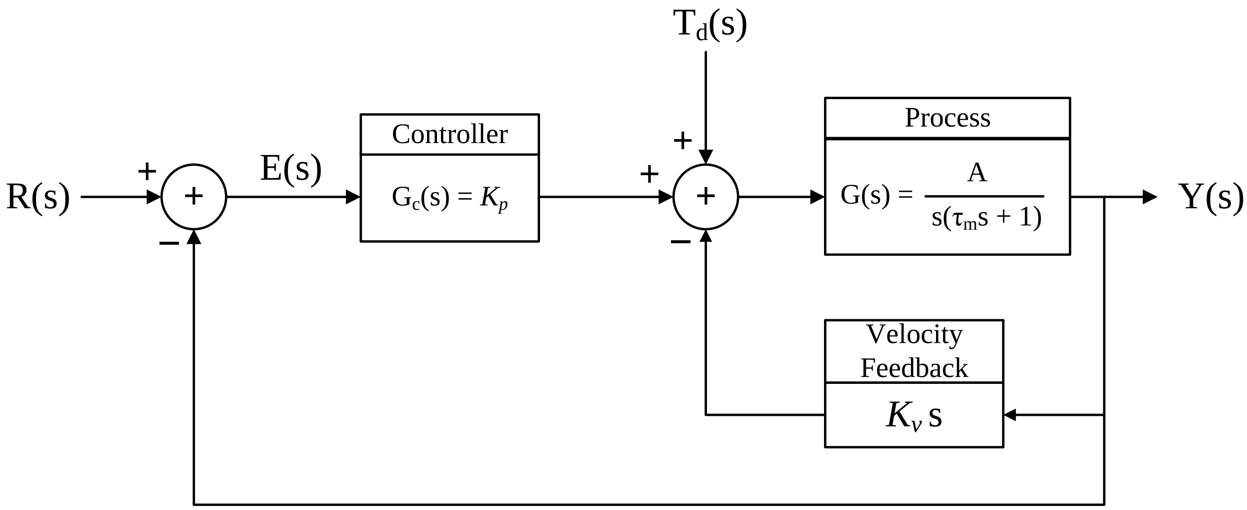

Figure 3: Proportional control of the DC servomotor with additional velocity feedback.

Pre-Lab Question 13 **(3 marks)** *Show that the damping ratio of the closed-loop poles is given by:*

$$\zeta = \frac{1 + K_v A}{2\sqrt{K_p A \tau_m}} \tag{17}$$

Pre-Lab Question 14 **(6 marks)** *How do the controller parameters K_p and K_v affect the settling time, the rise time, the maximum overshoot, and the steady-state error in response to a constant (step) disturbance?*

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4 Experiment 1: Proportional Controller Trade-off in Rise-time, Steady-state Error, and Percentage Overshoot (10 marks)

The proportional controller has one free parameter K_p. The pre-lab exercises examined the impact of this gain on several important performance measures, including the rise time, percentage overshoot, settling time, and steady-state error in response to a constant (step) disturbance acting upon the proportionally-controlled servomechanism. In particular, an inherent trade-off was exposed between the desire to have a small rise time, a small steady-state error to disturbance, and a small overshoot. In this experiment you will observe this trade-off with two different values of K_p using the following procedure:

i) Download the *Simulink starter file* from Avenue (Content > Laboratory > Simulink Starter File > EE3CL4_Lab.slx). You should create a separate folder for this lab on the computer. Place the starter file in the Lab 3 folder and name it appropriately (e.g., Lab3_Exp1).

ii) Open MATLAB, then Simulink, and open your Lab 3 Simulink file that was saved above.

iii) Find the *HIL Write Analog*, *HIL Read Encoder*, *Pulse Generator*, *Sum*, *Gain*, *Scope* and *To Workspace* blocks from the respective Simulink libraries and add them to the model. Follow Figure 1 to construct a feedback control system with proportional gain in the Simulink environment. Refer to the Lab 1 and Lab 2 manuals if you need more information on where to find these blocks and how to set them up.

iv) Model the *reference input* ($r(t)$ in time domain, which is shown as $R(s)$ in Laplace domain in Figure 1) by using a *Pulse Generator* block and set its *Amplitude*, *Period* and *Pulse Width* to 1.5, 6 and 50, respectively. This would set up the reference input $r(t)$ as a pulse train with amplitude of 1.5 radians or 85.94°, period of 6 seconds, and duty cycle of 50%.

v) Model the *disturbance* effect ($t_d(t)$ in time domain, which is shown as $T_d(s)$ in Laplace domain in Figure 1) by using another *Pulse Generator* block and use these settings in it: an amplitude of 0.1, period of 1000 seconds and duty cycle of 50%. This will create a *step disturbance* of 0.1 radians lasting a sufficiently long time.

vi) Open the *Gain* block representing the *Proportional Controller* (see Figure 4) and set its *Gain* to 1, i.e., $K_p = 1$. This is the first of two gain values that we will use in this experiment and will lead to an under-damped system (second-order). This *Gain* block is your controller.

vii) Open the *Gain* block at the output of the *Read Encoder* block which is meant to convert *Counts to Radians* (see Figure 4). Set its gain so that it receives *Counts* at its input and outputs position in *Radians* (Hint: You have already done this in Lab 1).

viii) We will run the motor only for 6 second intervals in this experiment. To do this, go to the *Modeling* tab in the Simulink window and then click on *Model Settings*. In the *Solver* tab and in the *Simulation time* area, set the *Stop time* to be 6 seconds. Click *Apply* and then OK. Save your Simulink model.

ix) When you are done building your model by following Figure 1, it should look like the target model shown in Figure 4. **STOP and VERIFY the following (Failure to do so may lead to damaging your motor):**

- Have you converted *counts* to *radians* (Step vii above)?
- Make sure that the closed-loop is set as a negative feedback loop.

x) Turn ON the Qube-Servo 3 motor block using its ON/OFF button. Align the engraved line on the red circular load with the 0^o mark at the top of the Qube-Servo 3.

xi) In the Simulink window, go to the *Hardware* tab and press *Build* (found in the *Build, Deploy & Start* drop-down menu) to generate the Simulink model and then press the *Monitor and Tune* button to initiate the experiment.

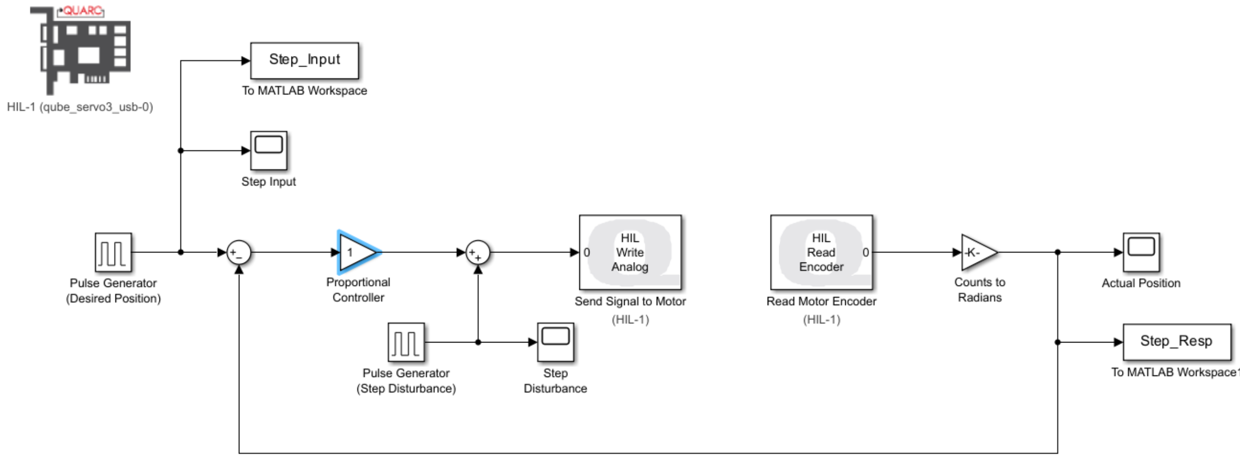

Figure 4: Target Simulink Model for Experiment 1.

xii) Send your data to the MATLAB workspace by using the *To Workspace* block and save it for at least one complete step response period so that you can use it in your lab report. You will need to use the *save* command in MATLAB to do so. Ask the TAs for help, if required.

xiii) Now measure the following three parameters: 1) 10%-90% Rise time; 2) Percentage Overshoot; 3) Steady-state error. You can do so either by using cursors in Simulink plots or by working with data that you exported to MATLAB.

xiv) Again open the *Gain* block representing the *Proportional Controller* and now set its *Gain* to 5, i.e., $K_p = 5$. This is the second of two gain values that we will use in this experiment and will also lead to an under-damped system (second-order).

xv) Re-run the experiment, again send your data to MATLAB workspace and save it. Again measure the following: 1) 10%-90% Rise time; 2) Percentage Overshoot; 3) Steady-state error.

xvi) Turn OFF the Qube-Servo 3 motor.

With your lab partner, discuss the impact that increasing the proportional gain K_p had on the 10%-90% rise time, percentage overshoot, and steady-state error.

At this point, you should call the Teaching Assistant to have your Experiment 1 evaluated. **Note**: To earn marks for your performance in this experiment, you need to demonstrate the step responses of the system to your TA and explain the impact of changing the value of K_p on rise time, percentage overshoot, and the steady-state error due to the step disturbance. **Your report should include plots of the step response for the two K_p values used, and your observations and analysis of the system response in the context of predictions made through the theoretical analysis in the pre-lab.**

5 Experiment 2: Proportional Servo Controller (10 marks)

The single design parameter in the proportional controller, K_p, allows you to independently adjust for one of the closed-loop step response characteristics at a time (with the exception of settling time). In this experiment, we will focus on how K_p impacts two of these step response characteristics for under-damped systems, namely, percentage overshoot and steady-state error due to a step disturbance, one at a time. Specifically, you will select K_p to achieve the following:

- Produce an *under-damped* step response with a percentage overshoot of less than 20%. First theoretically calculate the required value of K_p by using the work that you did in the Pre-lab and then use that K_p value in your Simulink model. Once you achieve the percentage overshoot requirement, determine the steady-state error (due to a step disturbance) for this choice of K_p.

- Produce an *under-damped* step response with a steady-state error (due to a step disturbance) that is less than 1% of the magnitude of the step reference input. Again you will need to select a value of K_p that will fulfill this steady-state error requirement. You can do so by using your work in Pre-Lab Question 10 since in this case the height of the disturbance, τ_d, is known. However, in practice, the disturbance is not exactly known. Thus, you can also experimentally determine the K_p value that will lead to the required steady-state error by picking various gain values in the range: $0.5 \leq K_p \leq 7$, and then selecting the one that leads to $e_{SS} < 1\%$. Once the steady-state error requirement is achieved, determine the percentage overshoot for this choice of K_p.

For the above scenarios, especially the percentage overshoot one, you will need to use the DC motor system parameters, gain A and time constant τ_m identified in Lab 2, in your theoretical calculations. **Use the A and τ_m parameter values that you obtained using the *Time Domain* approach in Lab 2. This also means that you must use the same workstation as you did in Lab 2.** Starting with the model developed in Experiment 1, implement the proportional controllers for this experiment and observe the closed loop step response by following the procedure below. You need to examine the response of the system for both values of K_p calculated above.

i) Continue using the Simulink model that you constructed in the previous experiment (Section 4: Experiment 1) of this lab. Keep the *reference input* $r(t)$ and *disturbance input* $t_d(t)$ signals the same as in Experiment 1 (i.e., $r(t)$ Amplitude: 1.5 radians, Period: 6 seconds, Duty cycle: 50%; $t_d(t)$ Amplitude: 0.1 radians, Period: 1000 seconds, Duty cycle: 50%). And as in Experiment 1, ensure that the motor is run only for 6 second intervals (Modeling > Model Settings > Solver > Simulation time > Stop time).

ii) First perform the experiment to achieve a *percentage overshoot* of less than 20%. Open the *proportional controller Gain* block and enter the theoretically calculated value of the gain K_p for this case.

iii) Turn ON the Qube-Servo 3 motor block using its ON/OFF button.

iv) Press *Build* to generate the Simulink model and then press the *Monitor and Tune* button to initiate the experiment.

v) Send your data to the MATLAB workspace by using the *To Workspace* block and save it for at least one complete step response period so that you can use it in your lab report (Use the *save* command in MATLAB).

vi) Verify that you have achieved the required *percentage overshoot* requirement ($\leq 20\%$). Find the steady-state error due to the step disturbance as a percentage of the step reference input. For example, if the steady-state value of your step response (in the presence of a step disturbance) is 1.55 radians for a step reference input of 1.5 radians, then your steady-state error is 0.05 radians or 3.33% of your step reference input.

vii) Now repeat the experiment for the case where the steady-state error (due to a step disturbance) has to be less than 1% of the magnitude of the step reference input. Open the *proportional controller Gain* block and either enter the calculated value of the gain K_p as mentioned above or empirically select it by using different gain values in the range of $0.5 \leq K_p \leq 7$ and picking one that fulfills the steady-state error requirement.

viii) Re-run the experiment, again send your data to MATLAB workspace and save it. Verify that you have fulfilled the steady-state error requirement. Then find the *percentage overshoot* for this choice of K_p.

ix) Turn OFF the Qube-Servo 3 motor.

With your lab partner, discuss whether you can achieve a *percentage overshoot* of less than 20% and a *steady-state error* (due to a step disturbance) that is less than 1% of the magnitude of the step reference input, **at the same time, i.e., with one value of proportional gain K_p.**

At this point, you should call the Teaching Assistant to have your Experiment 2 evaluated. **Note**: To earn marks for your performance in this experiment, you must present the computations of the controller gains (K_p) for each of the two cases to the TA. You must also demonstrate the step responses of the closed-loop system with both these gains to your TA which show that you achieve the *percentage overshoot* and *steady-state error* requirements by selecting appropriate K_p values. **Your report should show that you were able to achieve the *percentage overshoot* and *steady-state error* requirements with appropriate K_p values and include relevant plots of the step response for the two K_p values used where one plot should show a response that achieves $\leq 20\%$ *percentage overshoot* while the other shows that the *steady-state error* due to a step disturbance is $\leq 1\%$. In your report you should discuss how you found the two K_p values (i.e., how you used your pre-lab work and work done in Lab 2 to achieve this). Finally, you should discuss (based on measurements that you obtained in this experiment) if it is possible or not to achieve both the *percentage overshoot* and *steady-state error* requirements with one K_p value.**

6 Experiment 3: Proportional Controller with Velocity Feedback (15 marks)

This part corresponds to Section 3 and Figure 3. Hopefully, by now you would have realized that it is impossible to achieve competing design requirements with just one parameter, i.e., through just the proportional controller gain K_p. In this experiment, you will add a *velocity feedback component* to your feedback control system and then select the controller gains K_p and K_v to simultaneously satisfy the following two design requirements:

- The magnitude of the *steady-state error* due to the constant disturbance input $T_d(s) = \frac{\tau_d}{s}$ is less than 1% of the magnitude of the step reference input $R(s) = \frac{\theta_d}{s}$. In our application we are using $T_d(s)$ to model the friction in the motor, and hence the actual value of τ_d for the motor that you are working on is unknown. Therefore, the gain K_p that achieves this objective needs to be determined experimentally.
- The *percentage overshoot* in the step response is less than 10%.

Design and evaluate the controller response by following the steps below:

i) Copy the Simulink model file that you developed for the previous parts of this lab and save it as a new Simulink model for this part (so that your earlier work remains preserved).

ii) In the new Simulink file for this part, in addition to the blocks already added in earlier experiments in this lab, find the *Derivative* block from the Simulink library and add it to the model. Also add another gain block.

iii) Follow Figure 3 to build the required feedback control system, with velocity feedback, in the Simulink environment. When you are done building your model by following Figure 3, it should look like the target model shown in Figure 5.

iv) Model the *reference input* $r(t)$ and *disturbance input* $t_d(t)$ signals the same as in Experiments 1 and 2 (i.e., $r(t)$ Amplitude: 1.5 radians, Period: 6 seconds, Duty cycle: 50%; $t_d(t)$ Amplitude: 0.1 radians, Period: 1000 seconds, Duty cycle: 50%). And as in Experiments 1 and 2, ensure that the motor is run only for 6 second intervals (Modeling > Model Settings > Solver > Simulation time > Stop time).

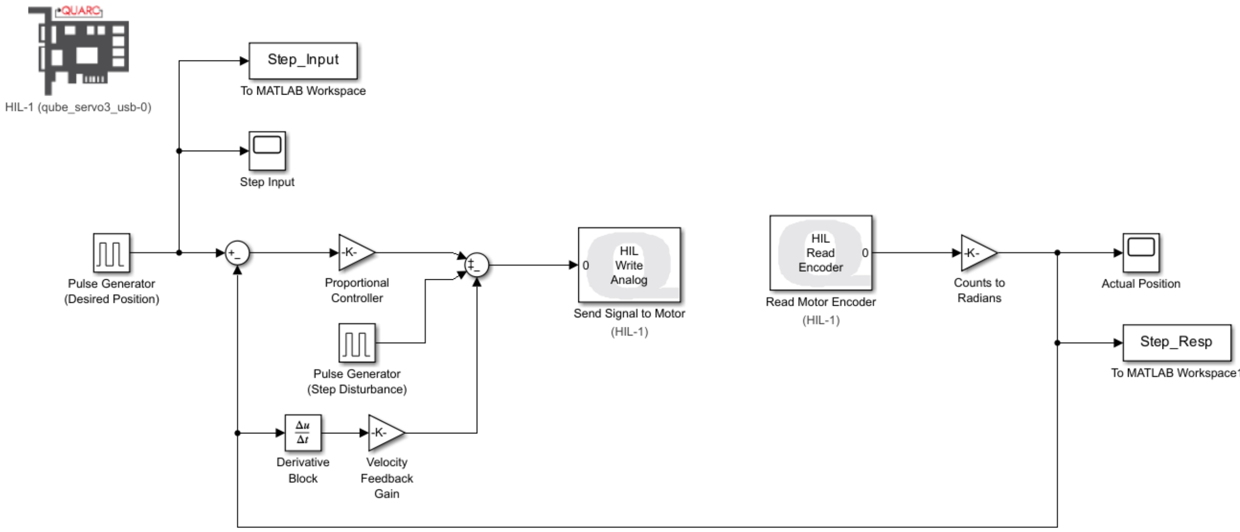

Figure 5: Target Simulink Model for Experiment 3.

v) Press *Build* to generate the Simulink model.

vi) Open the *Gain* block for the *proportional controller* K_p and pick it in the range: $0.5 \leq K_p \leq 7$. Open the *Gain* block for *velocity feedback* K_v and set $K_v = 0$.

vii) Turn ON the Qube-Servo 3 motor block using its ON/OFF button.

viii) Press the *Monitor and Tune* button to initiate the experiment.

ix) Repeat Step (vi) with different values of K_p and re-run the experiment until the steady-state error due to the step disturbance is less than 1% of the desired angular position of 1.5 radians (i.e., $e_{ss} < 0.015$).

x) For the final value of K_p obtained in the above step, send your data to the MATLAB workspace by using the *To Workspace* block and save it for at least one complete step response period so that you can use it in your lab report. Also, make a note of the maximum *percentage overshoot* with $K_v = 0$.

xi) For the value of K_p determined experimentally above, theoretically compute K_v using the result in Eq. (17) to satisfy the *percentage overshoot* requirement (< 10%). To do so, you will need to use the DC motor system parameters, gain A and time constant τ_m, identified in Lab 2. **Use the A and τ_m parameter values that you obtained using the *Time Domain* approach in Lab 2. This also means that you must use the same workstation as you did in Lab 2.**

xii) Now run the experiment with the values of K_p and K_v obtained in the previous steps.

xiii) Send your data to the MATLAB workspace by using the *To Workspace* block and save it for use in the report.

xiv) Turn OFF the Qube-Servo 3 motor.

With your lab partner, discuss whether you were able to achieve a *percentage overshoot* of less than 10% and a *steady-state error* (due to a step disturbance) that is less than 1% of the magnitude of the step reference input, **at the same time, i.e., with one set of gains K_p and K_v**. Contrast this to Experiment 2 where your only design parameter was K_p.

At this point, you should call the Teaching Assistant to have your Experiment 3 evaluated. **Note**: To earn marks for your performance in this experiment, you must present to your TA the values of the control gains, K_p and K_v, and explain how they were obtained. You must also show the step response of the final closed loop system, i.e., the one with both K_p and K_v which fulfills both the *steady-state error* and *percentage overshoot* requirements. **Your report must include a brief description of the control design approach with velocity feedback and plots of the step response of the system (one with K_p finalized and $K_v = 0$, while another with the final values of K_p and K_v that fulfills both the steady-state error and percentage overshoot requirements). Your report should also include the calculations through which you determined the final K_v value. Comment on whether both design requirements were met or not.**

7 Laboratory Report (25 marks)

Each group (of two students) must submit an electronic report through the Avenue to Learn Dropbox. Only one student in each group needs to submit the report in their Class section's Avenue to Learn Dropbox. The other student should verify the submission. The report is due by 11:59 pm five days from the day of your lab. For example, if your lab is on February 1, 2025, then your report would be due on February 8, 2025 at 11:59 pm. The report should be submitted as a PDF and formatted in single-column, single-spaced, using Times New Roman 12 or equivalent font. Both group members should state their individual contributions to the report in a statement in the beginning of the report. Both group members should clearly state their full names, student numbers, Lab section, and Class section(s) on the title page of the report. The report file should be named as: 3CL4_Lab_A_BB_Student1_Student2.pdf, where *A* is the lab number, *BB* is the lab section that the students belong to, *Student1* is the student number of the first student and *Student2* is the student number of the second student. A 10% penalty will be applied if the above-mentioned title page and/or file naming conventions are not followed.

The laboratory report must include plots of the results of the various experiments done in this lab followed by a brief analysis of the results, as instructed throughout this document. You must refer to the statements mentioned in bold and in dark blue color at the end of Experiments 1, 2, and 3 to determine what to include in the lab report. You should also briefly, in 1-2 paragraph(s), compare the two approaches of proportional control and proportional control with velocity feedback for the servomechanism.