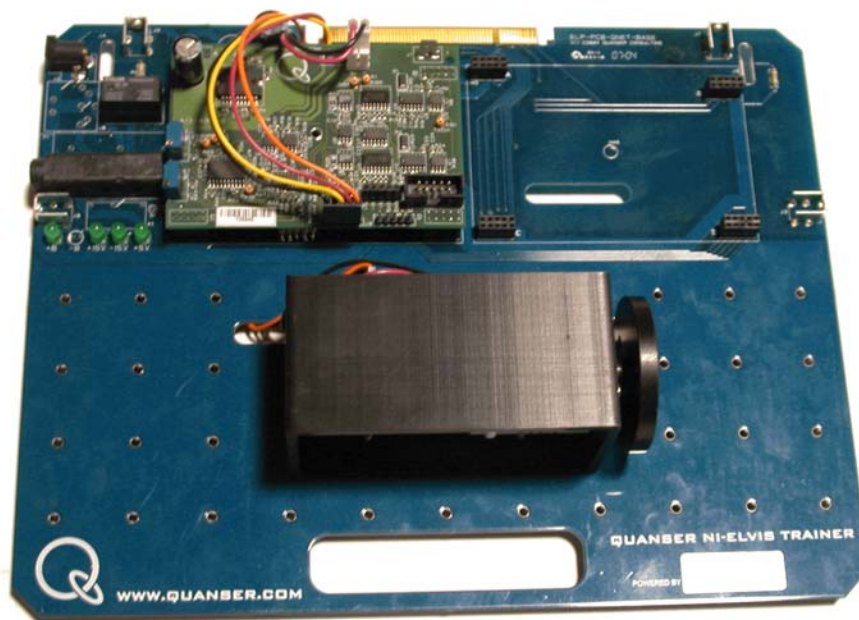




*Quanser NI-ELVIS Trainer (QNET) Series:*

# **QNET Experiment #02: DC Motor Position Control**

***DC Motor Control Trainer (DCMCT)***



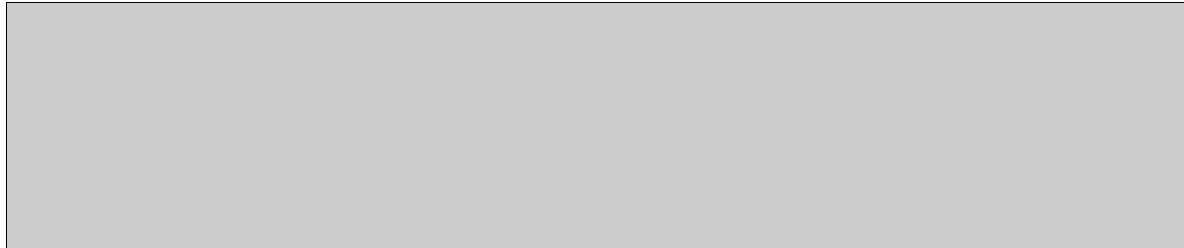
## **Student Manual**

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## 1. Laboratory Objectives

The objective of this experiment is to design a closed-loop control system that regulates the position of the DC motor. The mathematical model of a DC motor is reviewed and its physical parameters are identified. Once the model is verified, it is used to design a proportional-integral-derivative, or PID, controller.



## 2. References

- [1] *NI-ELVIS User Manual*
- [2] *DCMCT User Manual*
- [3] *QNET Experiment #01: DC Motor Speed Control*

## 3. DCMCT Plant Presentation

### 3.1. Component Nomenclature

As a quick nomenclature, Table 1, below, provides a list of the principal elements composing the DC Motor Control Trainer (DCMCT) system. Every element is located and identified, through a unique identification (ID) number, on the DCMCT plant represented in Figure 1.

<i>ID #</i>	<i>Description</i>	<i>ID #</i>	<i>Description</i>
<b>1</b>	DC Motor	<b>3</b>	DC Motor Case
<b>2</b>	Motor Encoder	<b>4</b>	Disc Load

Table 1 DCMCT Component Nomenclature

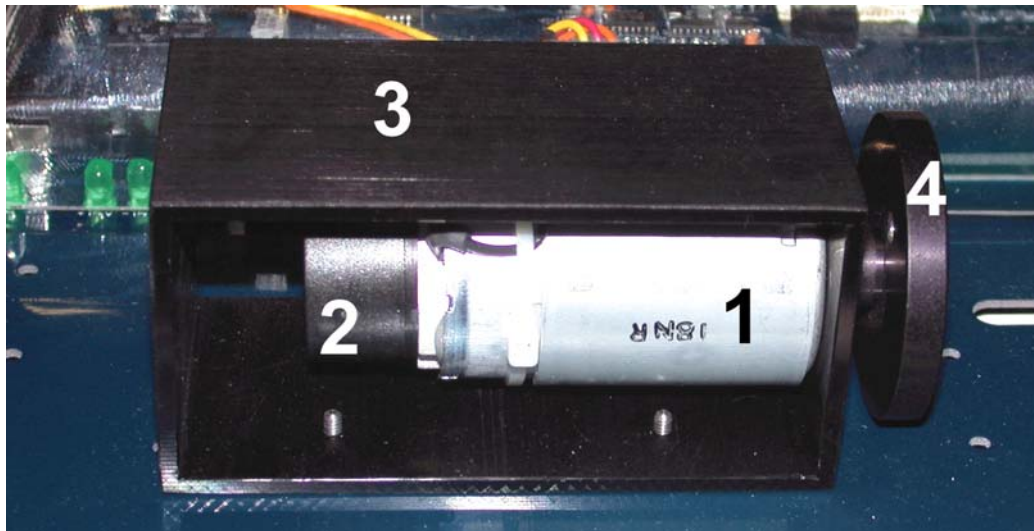


Figure 1 DCMCT Components

### 3.2. DCMCT Plant Description

The DCMCT system consists of a DC motor equipped with a servo motor driving a disc load. The motor input is a voltage with a range of  $\pm 24V$ . The motor has an encoder that measures its position, a digital tachometer that measures its speed, and a current sensor to measure the actual current being fed into the motor.

It is assumed that the QNET system is properly configured as dictated in Reference [1].

## 4. Pre-Lab Assignments



**This section must be read, understood, and performed before you go to the laboratory session.**

There are three pre-lab assignments that need to be completed before the in-lab session. The first exercise is deriving the open-loop model of the DC motor position. In Pre-Lab Exercise 4.2, a simple feedback system is used to analyze some properties of the DC motor system. The closed-loop system using a given controller is to be derived in Pre-Lab Exercise 4.3 and its control gains are designed to meet certain specifications in the last assignment (i.e. Pre-Lab Exercise 4.4).

Before beginning the exercises, the electrical and mechanical equations describing a DC motor are summarized and the model parameters used are given. For the various parameters

defined in Table 2, the electrical equations describing the open-loop response of the DC motor are

$$V_m(t) - R_m I_m(t) - E_{emf}(t) = 0 \quad [1]$$

and

$$E_{emf}(t) = K_m \left( \frac{d}{dt} \theta_m(t) \right) \quad [2]$$

The mechanical equations describing the torque of the motor are

$$T_m(t) = J_{eq} \left( \frac{d^2}{dt^2} \theta_m(t) \right) \quad [3]$$

and

$$T_m(t) = K_t I_m(t) \quad [4]$$

where  $T_m$ ,  $J_{eq}$ ,  $\omega_m$ ,  $K_t$ ,  $K_m$ , and  $I_m$  are described in Table 2. This model does not take into account friction or damping.

<i>Symbol</i>	<i>Description</i>	<i>Unit</i>
$V_m$	Motor terminal voltage	V
$R_m$	Motor terminal resistance	$\Omega$
$I_m$	Motor armature current	A
$K_t$	Motor torque constant	N.m/A
$K_m$	Motor back-electromotive force constant.	V/(rad/s)
$\omega_m$	Motor shaft angular velocity	rad/s
$T_m$	Torque produced by the motor	N.m
$J_{eq}$	Motor armature moment of inertia and load moment of inertia	kg.m <sup>2</sup>

Table 2 DC Motor Model Parameters

## 4.1. Pre-Lab Exercise #1: Open-loop Modeling

Derive the open-loop transfer function,  $G(s)$ , that represents the DC motor angular position with respect to the input voltage using equations [1], [2], [3], and [4]. The block diagram is shown in Figure 2.

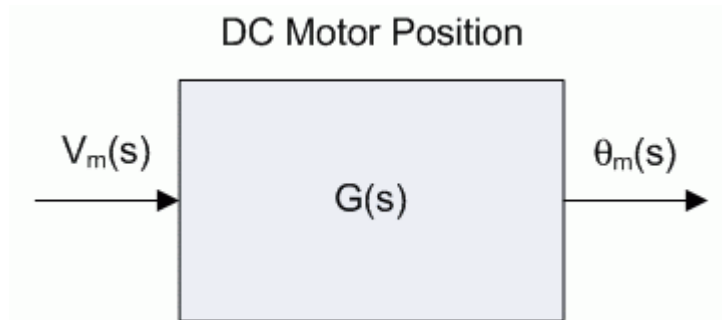
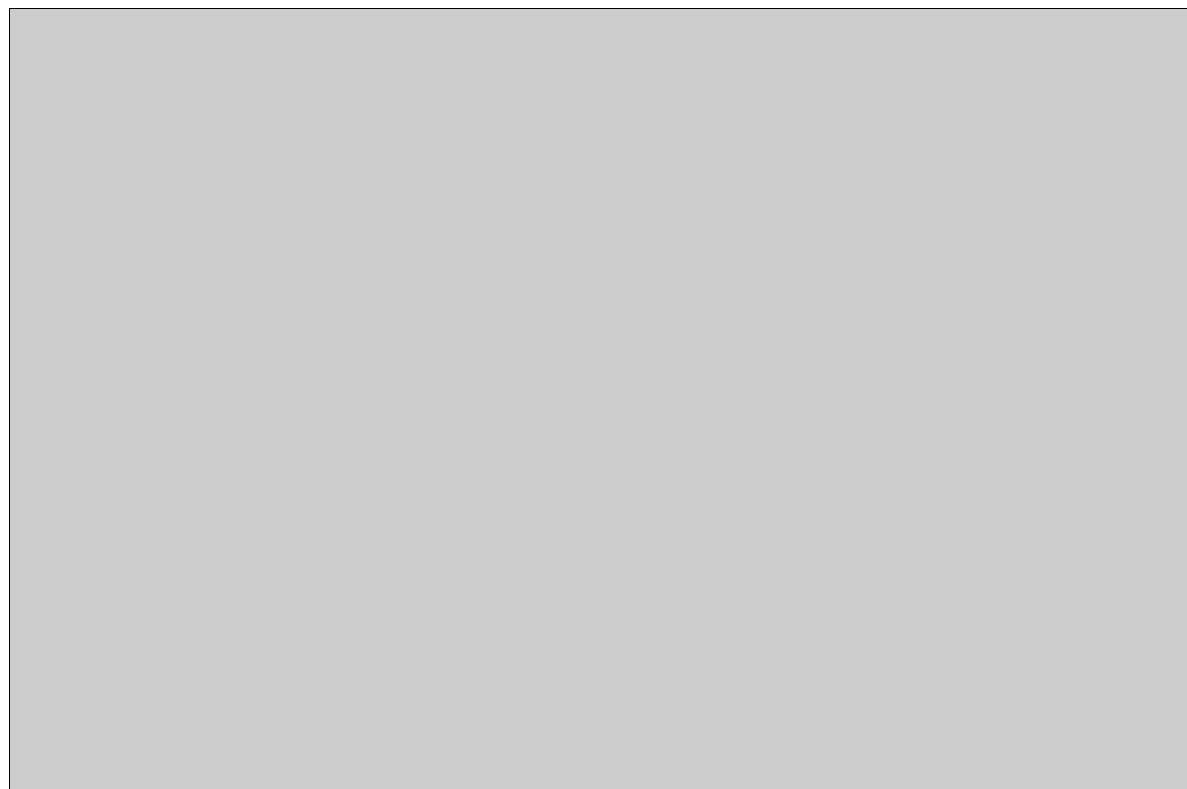


Figure 2 Open-loop Transfer Function Diagram of Motor Position



## 4.2. Pre-Lab Exercise #2: System Type

The transfer function developed in Exercise 4.1 is a mathematical representation of the DC motor shaft position and will be used to design a controller. Before designing the control system that will be implemented on the QNET-DCMCT module, the capability of the

position of the motor,  $\theta_m(t)$ , to track a reference position,  $\theta_r(t)$ , will be investigated.

Show that the unity feedback system shown in Figure 3 is a *Type 1* system. That is, for a unit step input

$$\theta_r(s) = \frac{1}{s}, \quad [4]$$

show that that the closed-loop system in Figure 3 has zero steady-state error. Note that  $G(s)$  is the open-loop transfer function of the DC motor, i.e.  $G(s) = \theta_m(s)/V_m(s)$ .

**HINT:** Calculate the error transfer function  $E(s)$  and find the steady-state error using the final-value theorem.

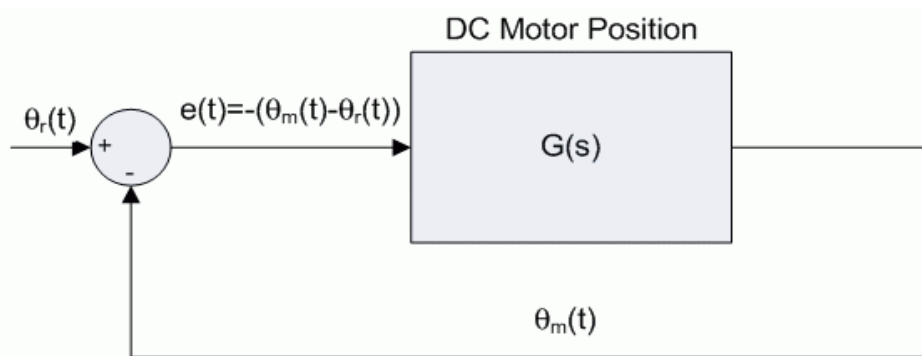


Figure 3 DC Motor Position Unity Feedback System





### 4.3. Pre-Lab Exercise #3: Closed-loop Transfer Function

The position of the DC motor is to be regulated to a desired setpoint position using a proportional-velocity (PV) controller, as shown in Figure 4. The control enters in the input voltage of the DC motor and has the structure

$$V_m(s) = -K_p (\theta_m(s) - \theta_r(s)) - K_v s \theta_m(s) \quad [5]$$

where  $K_p > 0$  is the proportional control gain and  $K_v > 0$  is the velocity control gain. This is very similar to the more common proportional-derivative (PD) controller which, instead, feeds-back the derivative of the *error* and not only the derivative of the position (i.e. the velocity). The PV controller is preferable in this case because it simplifies the peak time and overshoot calculations, which are done in the next exercise, and still results in good performance.

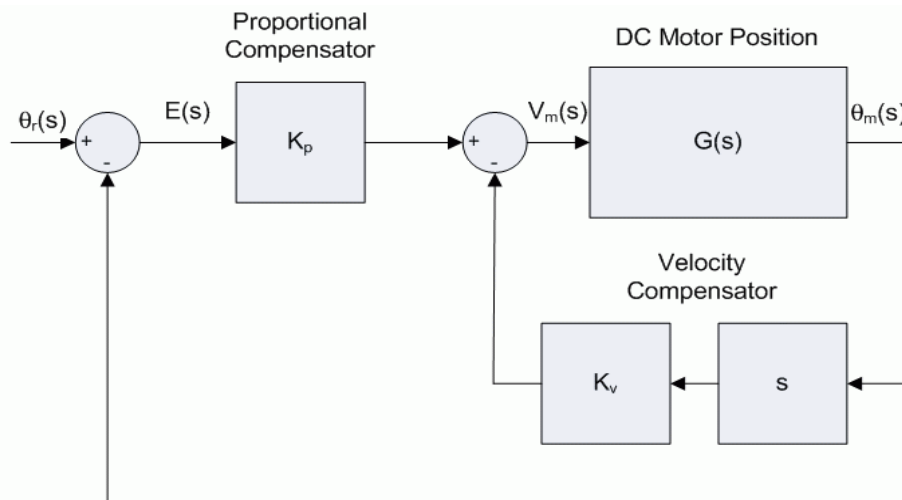
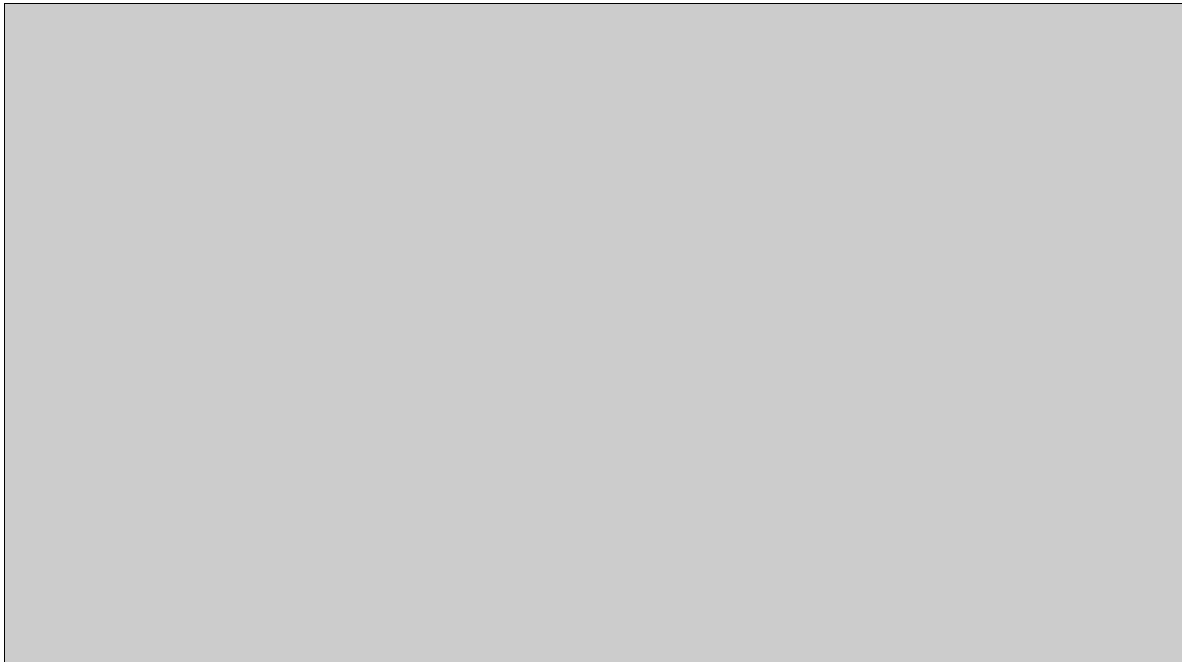


Figure 4 PV Control Loop

Find the closed-loop transfer function using  $G(s)$  found in Exercise 4.1 and the PV control law in [5]. Figure 4 may be used as a guide.

**HINT:** Refrain from substituting the open-loop transfer function  $G(s)$  until the final form of the closed-loop expression has been reached.



#### 4.4. Pre-Lab Exercise #4: Peak Time and Overshoot

The goal is for the angle of the disk load that is connected to the motor shaft to track a user-commanded angular position. The PV controller will be designed to result in a closed-loop response that yields to the specifications given in Table 3. This desired response is to be achieved by tuning the control gains  $K_p$  and  $K_v$ .

<i>Response Property</i>	<i>Symbol</i>	<i>Requirement</i>	<i>Unit</i>
Peak time	$t_p$	$< 0.150$	s
Overshoot	$M_p$	$< 5.00$	%
Settling time	$t_s$	$< 0.25$	s
Steady-state error	$e_{ss}$	0	deg

Table 3 Control Specifications

As shown in Exercise 4.2, the steady-state error of the closed-loop system is already zero. Thus the fourth specification, at least theoretically, is already satisfied. The settling time will be adjusted in the laboratory session.

The peak time and overshoot of the closed-loop response need to satisfy the specifications given in Table 3. The closed-loop transfer function using the PV controller, attained in Exercise 4.3, is a 2<sup>nd</sup> order system of the form

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad [6]$$

where  $\omega_n$  is the natural frequency and  $\zeta$  is the damping ratio. The peak time and overshoot of  $H(s)$  is

$$t_p = \frac{\pi}{\omega_n \sqrt{1 - \zeta^2}} \quad [7]$$

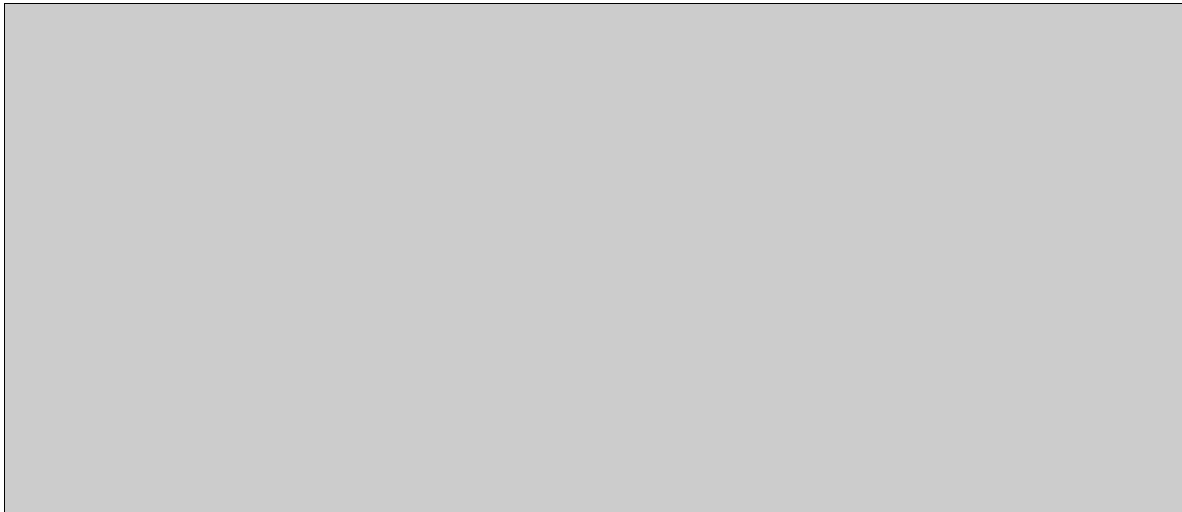
and

$$M_p = e^{\left(-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)}, \quad [8]$$

where  $0 \leq \zeta < 1$ .

The PV control gains are now to be designed. First, the natural frequency and damping ratio must be expressed in terms of the control gains and the DC motor parameters. The minimum damping ratio and natural frequency needed to meet the time peak and overshoot specifications in Table 3 can be calculated using equations [7] and [8]. Finally given that the minimum damping ratio and natural frequency is known and by solving for the  $K_p$  and  $K_v$  gains in the  $\omega_n$  and  $\zeta$  expressions derived, the PV gains needed to attain this desired closed-loop response can be found.

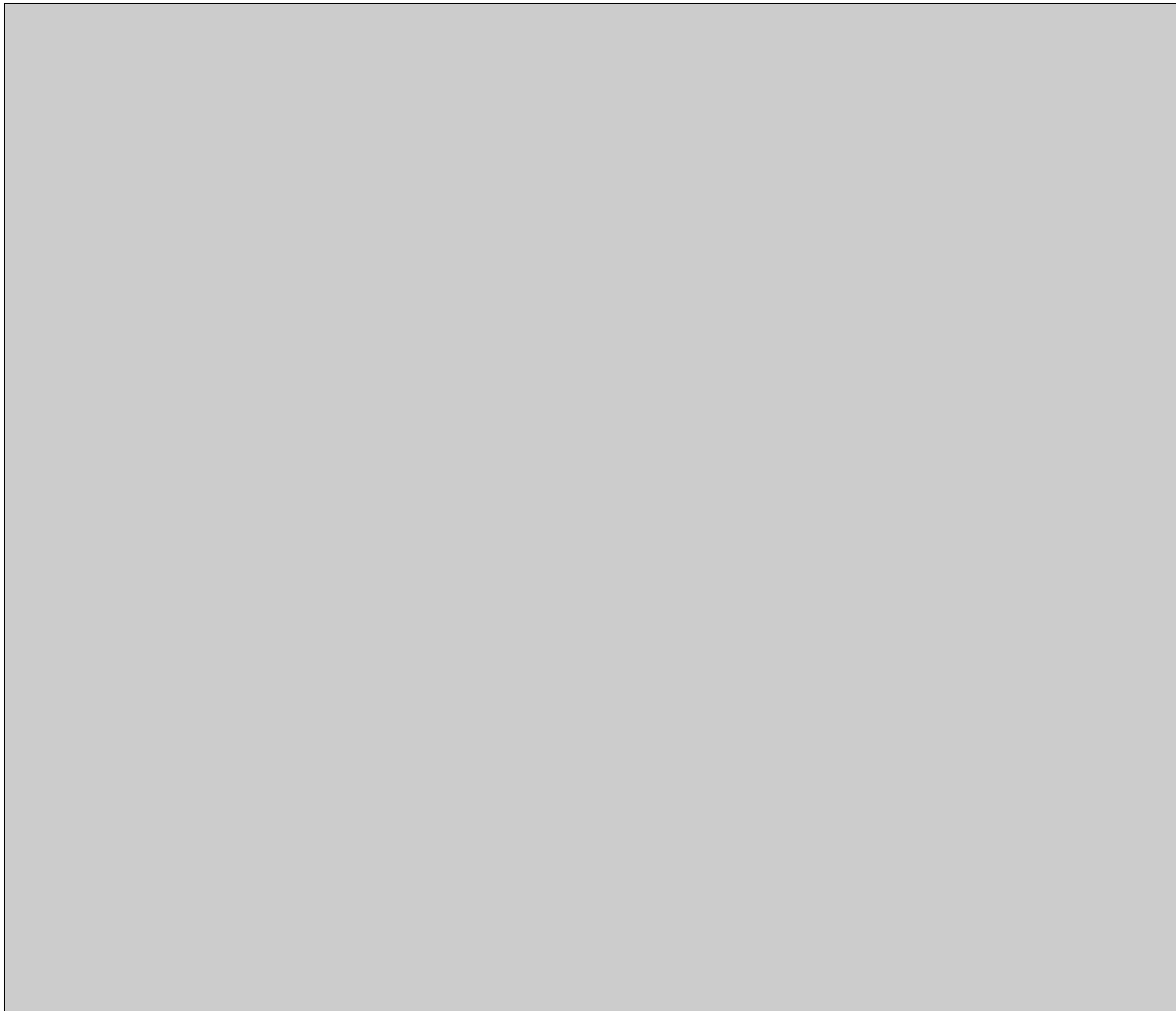
Find the natural frequency expression  $\omega_n(K_p)$  and the damping ratio equation  $\zeta(K_p, K_v)$  that results in the the closed-loop transfer function you found in Exercise 1.3 being equal to  $H(s)$  given in [6].



Find the minimum damping ratio required to satisfy the overshoot requirement in Table 3 using expression [8]. Then using  $\zeta_{\min}$  and peak time expression [7], find the minimum natural frequency needed to satisfy the peak time specification given in Table 3. Express both in terms of the model parameters and evaluate them numerically using the DC motor model parameters in Table 4.

<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>
$R_m$	Motor terminal resistance	2.50	s
$K_t$	Motor torque constant	0.020	N·m/A
$K_m$	Motor back-electromotive force constant	0.020	V/(rad/s)
$J_{eq}$	Motor armature moment of inertia and load moment of inertia.	2.00E-005	kg·m <sup>2</sup>

Table 4 Model Parameter Values for Exercise 4.4



Find the control gains needed to meet the specifications using the expressions found in the first part of this exercise and using the minimum damping ratio and natural frequency calculated above. Express  $K_p$  and  $K_v$  in terms of the model parameters,  $\omega_n$ , and  $\zeta$ , and give the numerical result of the control gains.



## 5. In-Lab Session

### 5.1. System Hardware Configuration

This in-lab session is performed using the NI-ELVIS system equipped with a QNET-DCMCT board and the Quanser Virtual Instrument (VI) controller file *QNET\_DCMCT\_Lab\_02\_Position\_Control.vi*. Please refer to Reference [2] for the setup and wiring information required to carry out the present control laboratory. Reference [2] also provides the specifications and a description of the main components composing your system.

Before beginning the lab session, ensure the system is configured as follows:

- QNET DC Motor Control Trainer module is connected to the ELVIS.
- ELVIS Communication Switch is set to BYPASS.
- DC power supply is connected to the QNET DC Motor Control Trainer module.
- The 4 LEDs +B, +15V, -15V, +5V on the QNET module should be ON.

### 5.2. Experimental Procedure

The sections below correspond to the tabs in the VI, shown in Figure 5. Please follow the steps described below:

- Step 1. Read through Section 5.1 and go through the setup guide in Reference [2].
- Step 2. Run the VI controller *QNET\_DCMCT\_Lab\_02\_Position\_Control.vi* shown in Figure 5.

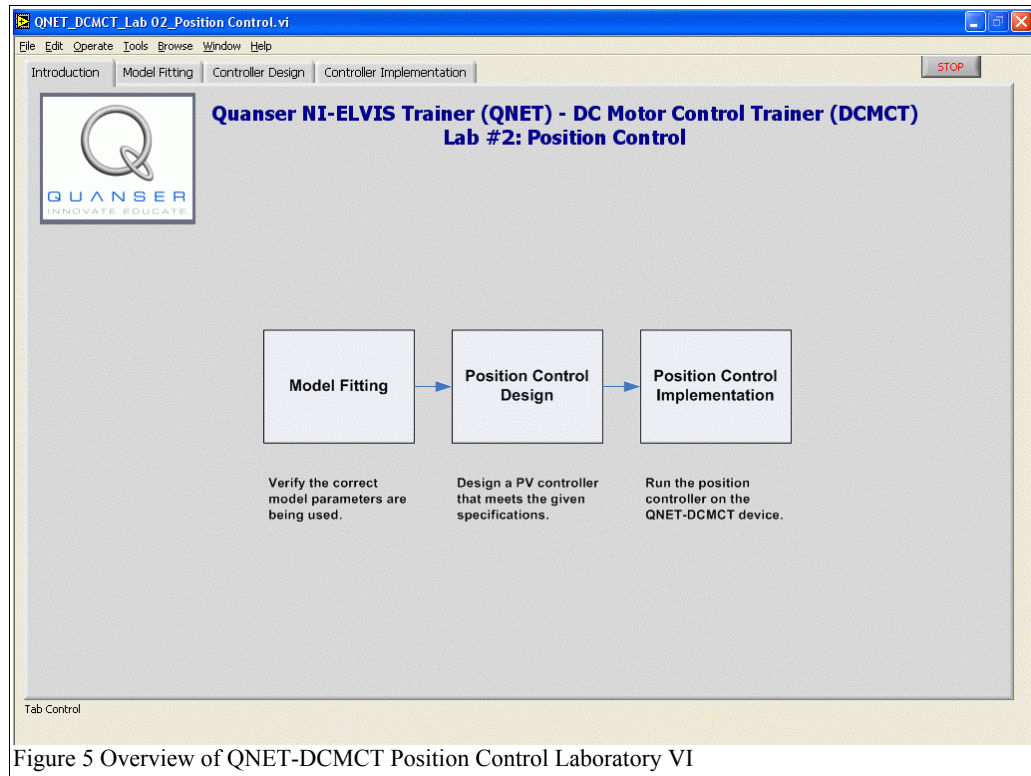


Figure 5 Overview of QNET-DCMCT Position Control Laboratory VI

- Step 3. In the previous laboratory, Reference [3], the three DC motor parameters given below were identified for a particular DCMCT unit:
- (1) **Motor Electrical Resistance ( $R_m$ )** – An electrical property of a motor. It describes the motor's response to a given voltage and determines the amount of current able to flow through the motor.
  - (2) **Motor Torque Constant ( $K_t$ )** – Describes the torque a motor generates and is directly proportional to the current going through the motor. Note that the electromotive force constant,  $K_m$ , is equal to the motor torque constant  $K_t$ .
  - (3) **Moment of Inertia ( $J_{eq}$ )** – The moment of inertia of the disc load and the motor shaft.

The three model parameters found in the last laboratory, Reference [3], may not represent the current DCMCT module being used accurately because a different QNET unit may be being used. For this reason, the model fitting procedure is redone to verify that the parameters in the transfer function developed in Exercise 4.1 represents the actual system.

- Step 4. Select the *Model Fitting* tab that loads the VI shown in Figure 6 and continue with the laboratory.



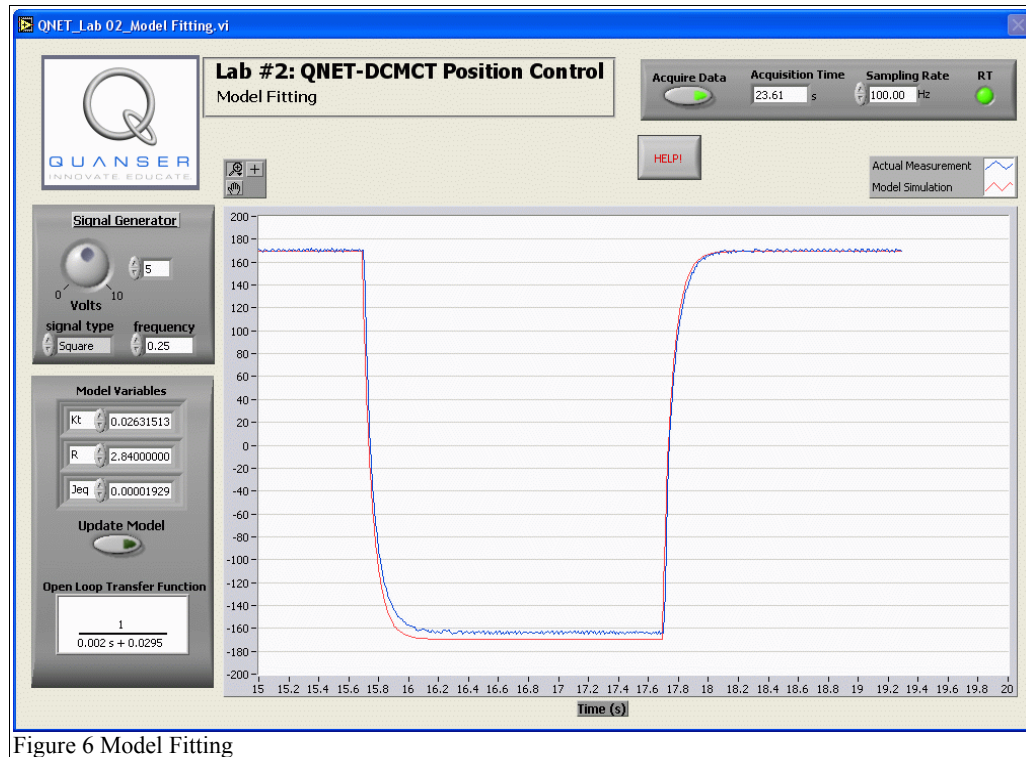


Figure 6 Model Fitting

- Step 5. As depicted in Figure 6, the scope displays the simulation of the motor speed response, generated using the mathematical model developed in the last laboratory, and the actual motor speed response, measured using the tachometer sensor. The QNET motor is being driven by the signal generator. The *Acquire Data* button stops the VI and continues to the next step of the laboratory. Also in the top panel shown in Figure 6 is the simulation time readout, the sampling rate, and the *RT* LED that indicates if real-time is being held.



**Slow down the sampling rate if the RT LED is either RED or flickering between GREEN and RED.** For the new sampling rate to take effect, stop this controller by clicking on the *Acquire Data* button and return to the *Model Fitting* tab to reload this sub-VI.

- Step 6. Enter the parameters  $R_m$  and  $K_t$  into the model variables that were derived in the DC motor speed control laboratory, Reference [3]. Select the *Update Model* button and notice that the simulation on the plot changes because it is simulating the system using the model with new parameters.
- Step 7. If there is a large discrepancy between the plots then a different QNET-DCMCT module is being used than the system used to perform the parameter estimation in the previous speed control laboratory. Adjust the motor torque



constant,  $K_t$ , the motor resistance,  $R_m$ , and the inertia parameter,  $J_{eq}$ , until the simulated response begins to match the actual response.

**Remember to click on the *Update Model* button after changing a model parameter for the changes to take effect in the simulation.**

- Step 8. Once the simulation matches the actual response well, record the final  $J_{eq}$ ,  $K_t$ , and  $R_m$  used in Table 5 and click on the *Acquire Data* button to proceed to the control design.

<i>Model Fitted Parameter</i>	<i>Measured Value</i>	<i>Unit</i>
$R_m$		$\Omega$
$K_t$		N·m/A
$J_{eq}$		kg·m <sup>2</sup>

Table 5 Model Fitted Parameters

- Step 9. The *Controller Design* tab should now be selected. As shown in Figure 7, the *Motor Model* block is the transfer function representing the open-loop system, the proportional and velocity compensators together compose the PV control system, as in *Pre-Lab Exercise 4.3*. By default, the reference input signal is a step of 90 degrees and the resulting closed-loop step response is shown in the top-right corner. The natural frequency and damping ratio are indicated above the plot. Further, the closed-loop poles are plotted on the s-plane in the middle graph of the VI and the locations of the poles are also given directly above the graph. Note that the locations of the poles is directly related to the damping ratio and natural frequency, which effects the resulting closed-loop response.

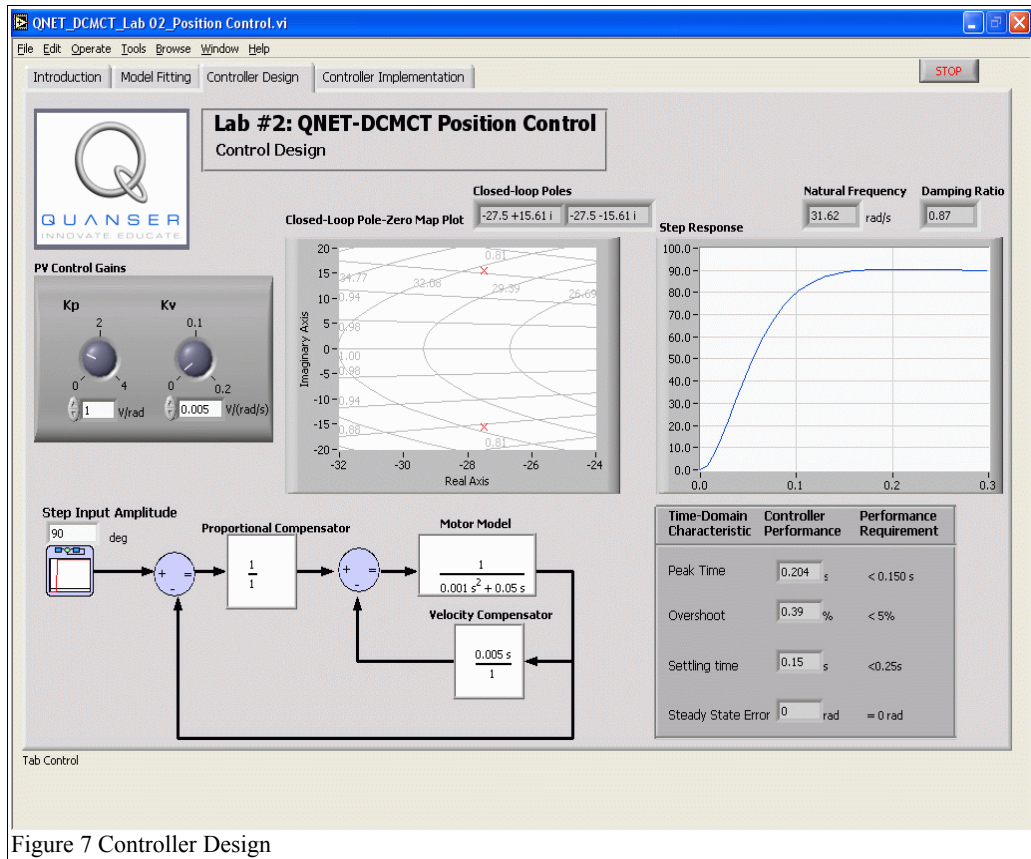


Figure 7 Controller Design

Step 10. The two control knobs in Figure 7 change the proportional gain,  $K_p$ , and the velocity gain,  $K_v$ , of the controller. Vary the gains  $K_p$  and  $K_v$  as listed in Table 6 and record the *Controller Performance* changes.

$K_p$ (V/rad)	$K_i$ (V.s/rad)	Peak Time (s)	Max. Over- shoot (%)	Setting Time (s)	Steady-State Error (%)
0.5	0.0025				
1.00	0.0025				
2.00	0.0025				
1.00	0.01				
1.00	0.0200				
1.00	0.1000				

Table 6 Controller Performance

- Step 11. Re-calculate the minimum control gains in *Pre-Lab Exercise 4.4* needed to meet the specifications in Table 3 based on the model parameters of the current DCMCT module, recorded previously in Table 5. Record the PV control gains in Table 7.

Control Gain	Minimum Value to meet Specifications	Unit
$K_p$		V/rad
$K_v$		V/(rad.s)

Table 7 Required PV control gains for current DCMCT unit to meet specifications

- Step 12. Enter the minimum PV control gains calculated above in the  $K_p$  and  $K_v$  knobs in the *Control Design VI* shown in Figure 7. The resulting response should meet the specifications in Table 3 but some fine-tuning may be needed. The settling time was not accounted for in the design, thus the gains may have to be fine-tuned to meet the settling time requirement. Once the controller gains yield a closed-loop response that meets the required specifications, enter the  $K_p$  and  $K_v$  gains used in the last row of Table 6 along with the resulting response time-domain properties.
- Step 13. Select the *Controller Implementation* tab to load the VI shown in Figure 8. The controller designed is now to be implemented on the actual QNET DC motor system. The scope in *Controller Implementation VI*, as shown in Figure 8, plots the simulated motor position from the mathematical model using the parameters entered and the actual closed-loop position of the motor measured by the encoder.

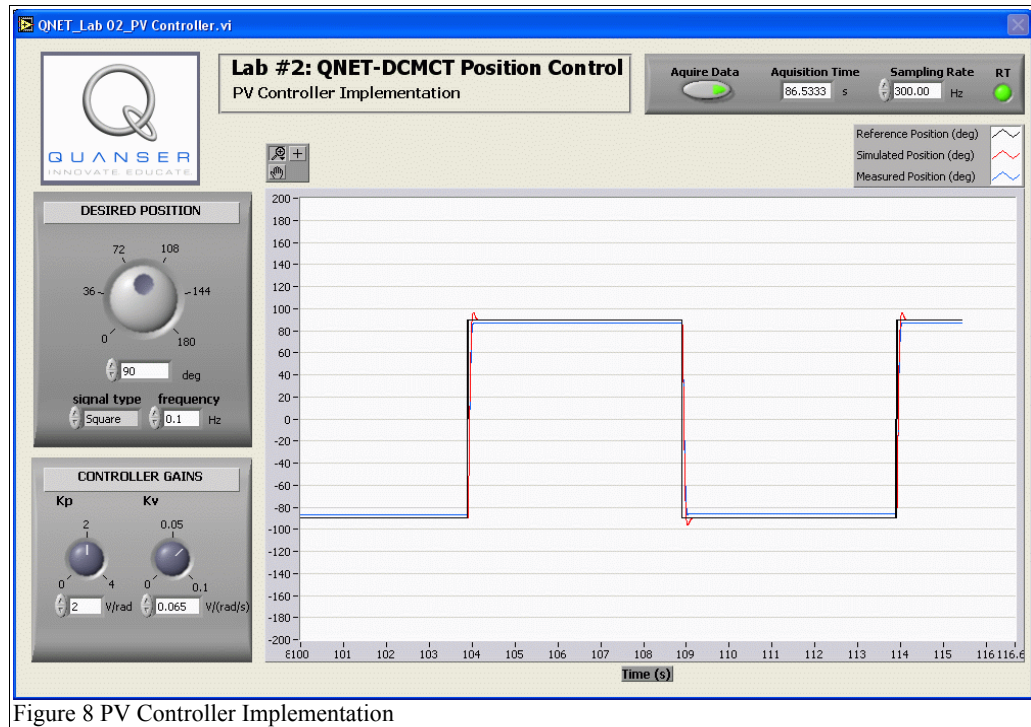


Figure 8 PV Controller Implementation

- Step 14. Ensure the proportional and velocity gains designed to meet the specifications, recorded in Table 7, are set in the *CONTROLLER GAINS* panel shown in Figure 8. The function generator in the *DESIRED POSITION* panel is used to generate the reference position. Set the commanded position signal to a square signal with an amplitude of 90 degrees at 0.1 Hertz.



**Implement the controller for the same system on which the model was obtained.** This ensures the controller is not based on a model that may not represent your motor.

- Step 15. Record the resulting control performance properties of the actual measured motor position – peak time, overshoot, settling time, and steady-state error – in Table 8. If needed, use the zoom tools in the top-left corner of the scope to view a closeup of the plots.

<b>Specification</b>	<b>Measured Value</b>	<b>Unit</b>
Peak time		s
Overshoot		%
Settling time		s
Steady-state error		deg

Table 8 Actual Closed-Loop Performance

- Step 16. Did the actual DC motor measurement meet all the specifications in Table 3? If not, give the specifications that were not met and provide an explanation why the PV control designed does not result in the desired properties when implemented on the actual system.

- Step 17. Change the amplitude, frequency, and/or type of reference signal (sine, sawtooth, and square) and observe the behaviour of the responses.
- Step 18. Stop the controller implementation by clicking on the *Acquire Data* button and this will send you to the *Mathematical Model* tab. Shut off the PROTOTYPING POWER BOARD switch and the SYSTEM POWER switch at the back of the ELVIS unit. Unplug the module AC cord. Finally, end the laboratory session by selecting the *Stop* button on the VI.