A Hardware Platform for Implementing Control Designs on the Quanser DC Motor Control Trainer

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Abstract
The paper describes hardware implementation of control system designs using the Quanser DC Motor Control Trainer (DCMCT). Toward this goal, students are guided to design control systems and verify their designs via simulation environments like MATLAB/Simulink. Then, they realize the control system designs by building op-amp circuits and validate the designs via the Quanser DC Motor Control Trainer. Through implementing the designed control systems in circuits, students learn how to physically design and implement a feedback control system.

1. Introduction
Control system design is a fundamental course for a variety of engineering majors, such as electrical engineering, mechanical engineering, chemical engineering and system engineering. Traditionally, control system courses have been taught with an emphasis on mathematics. Intuition and applications are ignored. As a result, most students only know how to calculate and plot parameters of a control system and vaguely understand the significance of the parameters. When they are engaged in practical control system designs, many students have no idea how to build a physical control system using available sources like circuits or microcontrollers and rarely apply the methods learned from the course to the applications. Under this circumstance, developing practical laboratory exercises are considered to be an essential approach in enabling students to understand control system designs in the real world. Furthermore, the laboratory exercises are an efficient approach to prepare students to work in industry [1].

In this paper, the development of laboratory exercises for control system designs courses has been discussed. The key issue is to let students comprehend the purpose of developing a feedback control system and the procedure of designing a practical control system. Therefore, several steps for laboratory exercises have been designed, for example, developing MATLAB/Simulink simulation solutions, modeling a physical system, permanent-magnet DC motor, from experiment data, designing and implementing a simplified control system in op-amp circuits, performing simulation and circuit implementation of motor velocity control and position control on the DCMCT trainer. After the laboratory exercises, a final project has been assigned to students to test if the students can apply the concepts of control system designs to practical systems. The results are generally satisfactory.

This paper will report the laboratory designs in the following steps. Since the Quanser DC Motor Control Trainer as a hardware platform has been intensively used, it will be introduced in Section2. Then, the laboratory designs will be discussed in detail and the results will be provided in Section3 and Section4, respectively. Section5 is the conclusions.

2. DC Motor Control Trainer (DCMCT)
Quanser Consulting Inc. of Markham, Ontario, Canada, is currently manufacturing the DC Motor Control Trainer which is shown in Fig.1. The hardware of the trainer contains a high quality Maxon DC motor, a linear power amplifier that allows a circuit to feed a control voltage to the motor, a potentiometer that reads the angular position of the motor, a tachometer (or encoder) that measures the angular velocity of the motor and a breadboard to prototype custom circuits.
Fig. 2 shows the schematic of the DCMCT board. From the board layout, we can see that the command, i.e., the voltage signal to control the DC motor, can be added through the command port. The angular velocity of the motor shaft will be measured through the tachometer output port and the angular position of the motor shaft can be measured from the current output port. Besides, the trainer rig can be operated and controlled by a PIC microcontroller through configuring an onboard jumper, J6. A computer software interface, named QIC (Quanser Interface Controller), allows students to observe the motor input/output and estimate system parameters using static and dynamic measurements through a PC computer. A comprehensive review for the Quanser Engineering Trainer can be found in [2][3].

3. Organization of Laboratory Exercises
Students who enroll the linear control systems course are supposed to be engineering undergraduates in junior or senior level. They should have successfully completed a high-level programming course, as well as introductory courses for circuits and electronics. For the course of linear control system laboratory, students need to learn a software package which is easier for students to simulate control system designs, select control system parameters and predict the experimental results. Toward this target, MATLAB/Simulink environment is chosen [4]. Therefore, in the first two or three laboratory periods, students are guided to use MATLAB, especially SIMULINK, to solving differential equations and drawing transfer functions, observing the system responses under the different types of inputs, such step function, ramp function and parabolic function.

After they are familiar with the design and simulation tool, the laboratory exercises are arranged in the following steps.

1) Permanent-Magnet DC Motor Modeling
To model the DC Motor, students are required to describe the operation of the DC motor using first principles. Then, they apply first principles to develop a second order linear mathematical representation of the armature controlled DC motor that models the effect of armature voltage and load torque on motor velocity and position. Next, they calculate a simplified first order model of the armature controlled DC motor.

In the laboratory, they feed input voltages to the DC motor on the DCMCT trainer, hold the motor shaft and measure the current of the motor. The voltage and the measured current are used to calculate the resistance of the armature circuit. Next, they obtain the back EMF (Electro Motive Force) constant by add-
ing input voltages and measuring both the current and angular velocity of the motor. Having gaining all necessary parameters, students can derive the first order model of the DC motor. The derived model is verified by dynamic measurement of parameters of the first order model, i.e. inputting voltages to the DC motor and measuring the angular velocity of the DC motor. Based on the system response curve, the time constant and the steady state value of the first order model are estimated.

The parameter measurement of the DC motor is completed with the help of the QIC software package along with the DCMCT board.

2) Simplified Control System Designs using OP-AMP Circuits

The second step of the hardware implementation is to let students realize the performance of a physical system, such as a DC motor, can be changed by connecting the system to a circuit and adjusting the parameters of the circuit. As shown in Fig.3, since the model of the DC motor can be described by a first order transfer function, we can use an op-amp with the electrical components, such as a resistor and a capacitor, to represent it. Then, the circuit is serially connected to another op-amp circuit. The output of the circuit is used as a feedback signal to feed the third op-amp circuit so that a negative feedback path can be built.

By adjusting the feedback gain, the system response can be faster or slower. Therefore, the feedback gain of the circuit is required to be calculated so that a specification, or say a desired system response, can be obtained. The specification is provided by the time response in a second order system, i.e. the requirement for overshoot, peak time, rise time and settling time [5].

3) Implementation of Velocity Feedback Control using OP-AMP Circuits

This laboratory exercise helps students understand how to model the velocity measurement sensor, tachometer, by feeding the motor voltage signal and measuring the angular velocity in radians per second and voltage, respectively. In particular, students are required to examine the difference of the velocity responses of the DC motor between open-loop and closed-loop with the presence of loading, i.e. a weight of 50g is hung on the motor pulley (see Fig.4.), or without loading.

a) Open-loop angular velocity control of the DC motor
In the experiment, students generate a reference signal in square waveform and feed the signal to the motor and observe how the motor angular velocity follows the input through an oscilloscope. A typical angular velocity response is shown in the left side of Fig. 5.

![Fig. 5. Angular velocity responses of DC motor in open loop (Left: unload; Right: load)](image)

However, when the load is hung on the motor pulley, the angular velocity changes largely, which is shown in the right side of Fig. 5.

b) Closed-loop angular velocity control of the DC motor

Upon finishing the open-loop angular velocity control of the DC motor, students are required to build a circuit similar to the circuit in step 2), but without capacitors. The output of the circuit is fed into the motor and the output of the tachometer is used to feed into the op-amp circuit in the feedback path. Hence, a feedback control system has been built. Since a feedback loop will reduce the system gain, students need to think about it, mathematically derive the amount and adjust the reference signal so that the velocity response of the DC motor is similar to that in the open loop.

![Fig. 6. Angular velocity responses of DC motor in closed loop (Left: unload; Right: load)](image)

A typical motor angular velocity response is shown in the left side of Fig. 6, where the gain in both the forward path and the feedback path is 3. From the figure, we can see the system response is much faster than that in the open loop. Especially, when the same load is hung on the motor pulley, the motor angular velocity response almost does not change.

After the laboratory exercise, students are required to process the measured data and think what the advantages that a closed-loop velocity control system has. Especially, over a period of time control system
parameters and components deteriorate, how these variations have effected on a closed-loop feedback control system and an open-loop system based on their observations.

4) Implementation of Position Feedback Control using OP-AMP Circuits

The laboratory exercise is to study the position response of the DC motor to a "PD" (Propositional and Derivative) position control scheme. In order to design the control system via simulation, students need to model the position feedback sensor, potentiometer. Then, the effects of position and velocity feedback gains on the response of this second order system are examined.

In the laboratory, students are required to build the position feedback path using the output of the potentiometer and the velocity feedback path using the output of the tachometer. The feedback gain in the velocity path can be adjusted so that the optimal system response can be obtained. (In general, it is considered that the system response with 5% overshoot will be the optimal system response.)

![Diagram of position and velocity feedback paths](image)

**Fig.7.** Position (left figure) and velocity (right figure) feedback path design of DC motor control

When students complete the laboratory exercises, they need to compare the optimal feedback gain with the simulation result using MATLAB/Simulink. Typically, the simulation result will have a larger overshoot than the experimental result since some nonlinear factors, such as the dead zone in the potentiometer, have not been considered in the modeling. Besides, when the belt is used to connect the motor shaft and the potentiometer, since the motor will drive the rotary potentiometer, it can be considered as a load. Under the circumstance, students are encouraged to think and modify the simulation model so that a better simulation result can be obtained.

In addition, when students write the laboratory report, it is required that students analyze the effects of parameters, kp and kd, of the PD controller using the Root Locus method so that they can realize why we use the Root Locus technique to design a control system.

### 4. Results

Through the sequence of laboratory practices, the students learned (1) how to model a physical plant and sensors used in a control system; (2) how a feedback control system works, how to design a feedback control system and how to physically implement a feedback control system using electrical circuits; (3) how to validate control system designs via a DC motor control environment. The laboratory exercises have been used in Spring 2009, Spring 2010 and Fall 2010. After the exercise sections, a project has been assigned to students. Students are required to use the learned knowledge to design practice control systems. In the semester of Spring 2009, students were encouraged to find some control topics and implement the control projects in groups, such as water level control, inverted pendulum control, elevator con-
trol, power amplifier control, electromagnetic levitation system, and window curtain control. Most stu-
dents can articulately describe the basic concepts of control systems in their presentations and apply the
control methods learned from the course to solving the control system they had chosen. In the semester of
Fall 2010, the control system design has been conducted with the focus on the PID design since PID con-
trollers have been widely used in industry. In their final presentations, they can use what they learned
from the course, i.e. modeling systems, second-order system designs and the root locus method to design
a PID controller and implement the PID design to a DC motor control system.

5. Conclusions
The paper has presented circuit implementations of control system designs on the Quanser DC motor con-
trol trainer. Through the hardware implementation, students can clearly understand how a control system
works in the real world and be able to design a control system, conduct simulations to verify the design
and realize the control system via circuit designs. Other benefits from the hardware implementation of
the control system designs are (1) it provides an opportunity for students to apply the knowledge learned
from the courses like circuits and electronics to solving practical problems in engineering; (2) it enhances
students’ ability for trouble-shooting and system analysis, which are of significance for students to be suc-
cessful in later senior design projects, advanced courses or their jobs in industry.

6. References
Control Education, Madrid, Spain, June 2006.
2005.
Laboratory Experience for Undergraduate Students: Toward Standardization and Shared Resources,”