The Quanser DC Motor Control Trainer

Individual or team learning for hands-on control education

by Dennis S. Bernstein

Anyone who teaches engineering is well aware of the economic demands of a laboratory course versus a lecture course. A lecture course can grow in size (at least to a reasonable extent) with minimal effect on the students and little marginal expense to the educational institution. A lab course, on the other hand, requires facilities in terms of benchtop equipment and lab space. One solution for accommodating a large lab class is to have students work in teams. In fact, in recent years there has been a widespread effort to promote "team projects" in engineering curricula based on the belief that team experiences build skills that are important for a professional career.

Lab Space and Teamwork

My personal experience, both from my own education and observing students, is that teams do indeed build students' skills in working in a group environment, but at a cost. The cost is that, within a given team, students naturally gravitate to those tasks that they do best. Students skilled at setting up and running experiments will perform, and improve, at that task, while students skilled at writing reports will likewise gravitate to that task. Hence, the down side of teams is that students often fail to develop those skills that are in greatest need of improvement.

The DC Motor Control Trainer (DCMCT), as part of the Quanser Engineering Trainer series (QET, pronounced "kwet"), represents a radically innovative approach to solving both a shortage of lab space and lack of variety in individual student lab experiences.

Quanser's solution, described in [1], is as simple as it is innovative: Shrink the experiment so that it fits in a lightweight attaché case, provide a laptop interface, and let each student take the DCMCT home for a day of individually paced experimentation. This solution kills two birds with one stone: no lab space is needed, and every student gets the chance to work through every experiment. Of course, the DCMCT can be used by a team of students; in fact, the prelab assignments and DCMCT experiments provide enough material to keep a team of two or three students busy.

DCMCT Hardware

The DCMCT hardware consists of the board shown in Figure 1. The most evident feature of the QET trainer is the wheel attached to a dc motor with encoder. Serving a dual role, the wheel delivers an inertial load for experiments and provides a haptic interface. That is, the user can turn the wheel to provide inputs to the experiments while "feeling" torques provided by a virtual experiment. More on this feature later.
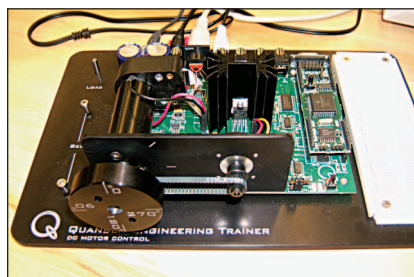
Figure 1. *The DC Motor Control Trainer (DCMCT) provides a sequence of motor control experiments for teaching the basics of classical control. The portable hardware allows students the opportunity to work through the experiments individually at their own pace.*

The dc motor is driven by a linear power amplifier. Linear amplifiers are less common nowadays compared with pulse-width modulated (PWM) amplifiers, which are more energy efficient. Presumably, the choice of a linear amplifier was made to overcome the deadband nonlinearity, limited bandwidth, and high-frequency noise associated with PWM amps. For a first lab course in control, this design decision was a wise choice. As discussed below, the DCMCT provides ample opportunity to experience the effects of nonlinearities from other sources.

In addition to the dc motor (a high-quality Maxon motor) with 12-b encoder, the DCMCT hardware includes an analog tach signal synthesized from the encoder, a servo potentiometer to provide an analog measurement of wheel angle, a breadboard for implementing analog controllers, and analog-to-digital converters (ADCs) for sampling the analog signals for digital control. The DCMCT includes a PIC microcontroller (called the QIC, pronounced "quick") for running embedded controllers. Controllers can also be run directly from a laptop or PC.

The interface to a PC or laptop is through a serial port connection, which requires an interface for newer laptops (about US$120). Quanser is reportedly developing a USB connection.

As is typical of many Quanser products, the hardware is especially "transparent." In other words, there is no attempt to package the circuit boards into hermetic containers adorned with switches and LEDs. Such packaging, although increasing the cost, would have the advantage of making the hardware more robust to coffee spills and dropped objects. On the other

hand, hiding the components from students would weaken the experience of working with real components and blur the distinction between hardware experiments and software simulation. For example, when the students analyze the effects of encoder quantization, they'll be able to see the device responsible for this effect. I'm a firm believer that engineering education should go beyond the computer screen whenever possible.

For transportation, the DCMCT hardware comes with a clamshell attaché case. The clamshell design removes any risk of picking up the case and inadvertently spilling its contents. (If you've ever picked up an attaché case without first locking it, you'll understand what I mean!)

DCMCT Software

The DCMCT comes with a CD that contains the complete manual (student and instructor versions, the latter with complete solutions) as well as all software needed for PC and laptop hosts. The QIC interactive interface (QICii) software package, shown in Figure 2, can be used to download code to the QIC, which performs the real-time control. The QICii (pronounced "quicky") also provides real-time communication with the QIC for parameter tuning, data collection, and plotting during operation.
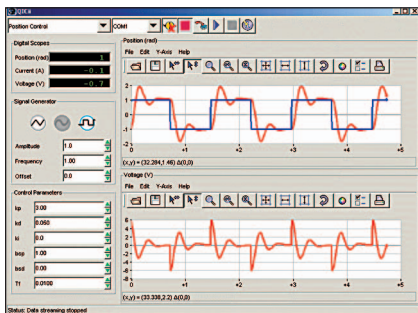
Figure 2. *QET interactive interface (QETii) software. The DCMCT software interface is based on GUIs that allow students to enter parameter values and view data in real time. The software was found to be robust with accurate documentation.*

All of the controllers needed for the experiments are precompiled in a form that allows parameters to be entered and varied. Third-party software (available separately) can be used to compile alternative controller structures.

The QET hardware can be used with a hardware-in-the-loop board (from various vendors) installed in a PC with real-time control software such as WinCon, Labview, or RTWT. The course and software supplied with the DCMCT do not require these tools, which minimizes system requirements and allows students to concentrate on control design rather than implementation.

Lab Modules

The DCMCT manual describes, in great detail, a total of five separate laboratory projects. For each project, the student must complete a prelab assignment before being allowed to check out the DCMCT. These prelab assignments require nontrivial time and effort in terms of analysis and computation. The output of each prelab assignment is a collection of numerical values that are needed to perform the associated experiment. Performing the more advanced prelab sessions requires the use of MATLAB or XMath.

Lab 1: Motor Modeling

The first prelab assignment involves motor modeling, in terms of both the basic physics and the derivation of linear models. Although this material is standard for students in mechanical engineering (ME), students in other disciplines may lack the necessary background to carry out the required steps. On the positive side, I believe that dc motor fundamentals should be part of every engineering student's education. For non-ME students, these prelab assignments can easily be replaced by in-class tutorials. In fact, for all of the subsequent projects, lectures could readily be structured to parallel and support the DCMCT prelab assignments and experiments.

The experiments corresponding to motor modeling involve both static and dynamic analysis. The static experimental analysis is used to confirm the results of the prelab assignment analysis, such as the motor resistance and torque constant. This experiment also focuses on the range of physical values that the motor can achieve, including maximum current, torque, and velocity. These calculations anticipate later discussions of saturation and anti-windup control. In addition, the static analysis also includes nonlinear effects such as Coulomb friction and encoder quantization.

The experimental procedures also include validating the dynamic models derived in the prelab assignment. Here, the interactive features of the software are especially convenient since the student can manually adjust the transfer function parameters to improve the step-response fit. Although this model-fitting procedure is not sophisticated, students benefit directly from the ability to adjust parameters and see the effect on model response. Discrepancies between best-fit parameter values and prelab analytical values can then be explained in terms of computational error, component tolerances, and other real-world effects.

A student can also interact with the hardware by touching the wheel gently while it is spinning, thereby introducing a load disturbance. An additional procedure is to assess the effect of unmodeled dynamics due to the neglected rotor inductance. Analysis shows that this element is dominated by an effective delay due to the 100-Hz sampling.

In this first assignment, the DCMCT has thus demonstrated static and dynamic motor modeling, static and dynamic model identification, the effect of nonlinearities (saturation, Coulomb friction, and quantization), and unmodeled linear effects due to sampling and neglected dynamics.

Lab 2: PI Control

Having completed analytical and experimental modeling of the motor in the first assignment, the students are now ready to undertake PI control for speed control. After a brief review of PI controller basics, the prelab assignment requires that the students tune PI controllers to achieve rise and settling time specifications. This analysis is based on the results of the modeling analysis and experiments in Lab 1. An excellent feature of the controller tuning is that the steps are carried out with a close eye on the saturation analysis in Lab 1. For example, in choosing a settling time for a change in speed setpoint, the student is asked to account for the acceleration limits due to current saturation. The linear control design process is thus guided by the analysis of nonlinear effects, which reflect hardware capabilities.

The prelab assignment also introduces integrator windup. A block diagram of a classic antiwindup technique is presented in advance of the experimental session. Additional prelab tasks involve tracking triangular reference commands and rejection of load disturbances.

For the experimental session, the student implements a P controller initially and examines the response, including the steady-state offset to a step command. Next, the student implements a pure I controller. After accounting for saturation effects, the student observes the rejection of load disturbances due to touching the wheel as it spins. The lab then continues with combined PI design, including Ziegler-Nichols tuning, setpoint weighting, antiwindup control, triangle wave tracking, and disturbance rejection.

Lab 3: Robustness

This lab investigates the effect of measurement noise and plant variations on closed-loop performance. The analysis focuses on the role of four key transfer functions, colorfully called the "gang of four," which for

"two-degree-of-freedom controllers," expand to the "gang of six."

The prelab assignment involves the analysis and computation of the sensitivity and complementary transfer functions, which are used to assess gain and phase margins. The analysis includes the effect of delays due to sampling. Students are asked to create Nyquist plots to display the robustness of the closed-loop system. In the experimental session, students follow a simple procedure for probing the system for gain margin, gain margin frequency, and gain crossover frequency.

Lab 4: PID Control of Position Control

In this lab, students experiment with PID controllers for the purpose of position control of the motor shaft. Performance limitations are accounted for in terms of the back electromagnetic frequency (EMF) and its effect on motor current. A peak power calculation is used to determine the minimum time required to achieve a given change in angle. This calculation is used to guide the PID design in subsequent steps.

Lab 5: Haptic Interface

In the final lab, students are given the opportunity to apply the skills obtained in the previous labs to a novel and fun set of experiments involving a haptic interface. Specifically, the student can control a virtual system by rotating the wheel while, at the same time, feeling an artificial torque applied to the wheel. The lab manual begins by providing a tutorial on impedance control, a topic not covered in standard control texts.

The experimental session first focuses on the Haptic Knob module, which consists of preprogrammed routines that make the wheel behave like a knob with detents (notches) of various types. Students find this feature surprising since they are well aware by now that the wheel and motor normally spin freely.

The wheel is then used as a user input device for controlling a simulation of a ball and beam, as shown in Figure 3. The student can control the ball and beam with or without a PD controller in effect. Various options allow the user to feel the ball position, ball speed, beam bump (beam hitting the table), and other effects. During these experiments, the student can "feel" the effect of the PD control during closed-loop operation. This lab concludes with an explanation of how the notched haptic knob operates in terms of a finite state machine model.

Logistics

The idea behind the DCMCT is that each individual student can check out the DCMCT for a day. The student can then work with the equipment wherever they wish, such as in a dormitory room or apartment. Quanser is fond of adding "in a café" to this list, but I would warn students about working with the hardware in the vicinity of open liquid containers.

With this check-out system, a total of six DCMCTs would be needed for a class of 40 students. This number is based on a seven-days-per-week schedule of hardware utilization. I would guess that weekend days would be popular for checking out the
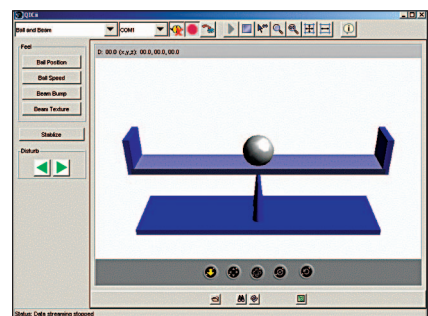
Figure 3. *Virtual ball and beam experiment. The haptic interface allows students to control the virtual ball and beam and "feel" a variety of effects. This application of control technology goes beyond the usual servo problems that traditionally comprise undergraduate control education.*

equipment since students don't typically have weekend classes.

To make this system work in practice, certain logistical problems would need to be addressed. First, it is necessary that the instructor or, more likely, a teaching assistant, check each student's prelab results to verify that the preassignment was done properly (and, of course, by the student claiming to have done the work). I would address this problem by assigning a common prelab report due date for all student. Next, checkout and check-in procedures would be needed to keep track of the equipment and verify its condition. There is always the possibility of loss or theft when equipment is used outside the departmental building. Policies would have to be in place to deal with these issues. Perhaps a locking and tethering mechanism would be a good investment. I would guess that students would want to check out the equipment in pairs, that is, one student would use the equipment and then pass it on to another student. This approach would work well (especially over weekends) as long as it did not undermine the goal of students working individually.

Evaluation and Conclusions

The QET Series in general, and the DCMCT in particular, represent an innovative approach to hands-on engineering education. Given a sufficient number of DCMCTs (number of students divided by seven), each stu-

dent will be able to have a day to work individually, at their own pace, with control hardware and software. In this manner, every student is assured the chance to have some hands-on experience with hardware and software.

The hardware is well constructed, and the software proved to be robust as my students and I worked through the labs. The manual was extremely accurate, with very few rough edges, a surprising achievement for a first release. The only hardware design change I would recommend is an increase in the gap between the lower edge of the wheel and the mounting plate, where thick fingers sometimes get caught. A minor design modification could easily fix this problem.

The projects that can be performed using the DCMCT do a fantastic job of illustrating practical control concepts. The DCMCT provides extensive experience with most of the classical control concepts, including the effect of plant variations and delays. In addition, linear design is guided by nonlinear effects,

such as saturation, friction, and quantization. I cannot recall seeing this kind of emphasis in any undergraduate textbook.

The prelab and experimental sessions are substantive and demanding. These tasks can be watered down or taken at full strength, depending on the audience. The last lab on the haptic interface is clearly the most fun, and the least demanding. I would view this lab as a well-earned "dessert" for students. Many students who reach this lab will be hooked on control. I would probably let students play with this feature up front as a kind of motivation for the work needed to appreciate its operation. Students will most likely play with this feature while having the equipment in their possession. Student will surely show the haptic experiments to their friends, thus providing free advertising for control education.

Having sufficient copies of the DCMCT to allow each student to work through the labs is an ideal situation, which, in my opinion, will pay enormous dividends in terms of student skill building and confidence. Although the logistics of letting students borrow an expensive piece of equipment must be worked out, the benefits will be considerable. I congratulate Quanser on a fine contribution to control education.

References

[1] J. Apkarian and K. J. Astrom, "A laptop servo for control education," *IEEE Contr. Syst. Mag.*, vol. 24, no. 5, pp. 70–73, Oct. 2004.

Analog Workout

[T]he Pepinsky computer… requires the crystallographer to take a trip around the laboratory turning little knobs before the machine is ready to go—and to repeat this trip whenever a variation of the problem is tried. Since the problem is solved by successive variations of the signs of appropriate coefficients in a multiple Fourier sum, the analysis of a structure involves a fair amount of exercise—a device for avoiding the sedentary habits of the academic profession which might be desirable.

—Mina Rees, "The federal computing machine program," *Science,* vol. 112, pp. 731–736, December 22, 1950 (reprinted in *Annals of the History of Computing*, vol. 7, no. 2, April 1985).