DC Motor Control Trainer (DCMCT)

Åström, Karl Johan; Apkarian, Jacob; Lacheray, Hervé

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1 AUTHOR:

K.J. Åström
Lund University

Quanser Engineering Trainer (QET) Series:

USB QICii Laboratory Workbook

DC Motor Control Trainer (DCMCT)

Karl Johan Åström
And
Jacob Apkarian, Hervé Lacheray

Student Workbook

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1. Introduction

1.1. Introductory Control Laboratories

Control is a very rich field with continuously increasing areas of applications. One reason for this is the beneficial properties of feedback. Feedback makes it possible to change the dynamic behaviour of a system, stabilization of an unstable system is a typical example. Feedback makes it possible to reduce the effect of disturbances. The major drawback is that feedback may create instabilities. The ubiquity of control makes it necessary to spread the knowledge of control to wider audiences. One of the conclusions in a recent panel [4] on control is the following recommendation: *Invest in new approach to education and outreach for the dissemination of control concepts and tools to nontraditional audiences.* The panel report goes on to say:

As a first step toward implementing this recommendation, new courses and textbooks should be developed both for experts and nonexperts. Control should also be made a required part of engineering and science curricula at most universities including not only mechanical, electrical, chemical, and aerospace engineering, but also computer science, applied physics, and bioengineering. It is also important that these courses emphasize the principles of control rather than simply providing tolls that can be used in a given domain. An important element of education and outreach is the continued use of experiments and the development of new laboratories and software tools. This is much easier to do than ever before and also more important. Laboratories and software tools should be integrated into the curriculum.

The experiments described in this booklet are inspired by the recommendations by the panel report. A control engineer should master theory and have a good understanding of practical control problems. The skill base includes tasks such as modelling, control design, simulation, implementation, commissioning, tuning, and operation of a control system [1], [2]. These skills are becoming more important today when control is ubiquitous [3]. Many tasks can be learned from books and computer simulations but laboratory experiments are necessary to obtain the full range of skills.

Introduction

The typical setup for control experiments consists of a physical process with sensors, actuators and power supply, a PC equipped with interfaces, and sometimes a DSP board. Control is performed using the DSP or the PC. The controller is either hand-coded (good luck!) or designed using commercially available design tools such as Simulink, SystemBuild, or LabVIEW. Once the design is performed, realtime code is generated and run on the PC using high performance realtime software such as WinCon, xPC Target, or LabVIEW RT.

This workbook is designed for an introductory course in controls. A first control course does not normally focus on practical issues. First time exposure to control typically focuses on the theoretical aspects. Special laboratory courses are offered as a complement to the theoretically-oriented courses but many students do not take such courses. This is unfortunate because good experiments can also be a strong motivation to pursue a career in controls.

Introductory courses in control with integrated labs are offered in most universities. Although integration of a lab has many advantages [5], [6], there is a difference between lectures and labs. A student can pick up a book or do a computer simulation at any time and at any place but experiments are heavily restricted in time and space.

This workbook focuses on a novel **portable** process that can be used with a laptop computer to investigate control system performance and evaluation. The system can be signed out by the student and taken home, library, or café, and thus eliminates the need for laboratory space. The system makes it possible to integrate theory and practice of control. The experiments can be done concurrently with studies of theory and computer simulation. This also makes it very suitable for practicing engineers who would like to brush up the knowledge of control.

The system is completely self-contained. The process consists of a DC motor and a PIC microcontroller that can be easily programmed to perform a series of control experiments of varying complexity. The process can be controlled using a laptop with no other software than that supplied with the system.

When designing the process and the experiments, we were guided by utility. Any user of control should have a good grasp of the fundamental ideas and concepts. It is therefore natural to include modelling, controller tuning, design, and robustness. The PID controller is by far the most common controller. We therefore made the decision to focus on PI, PD, and PID control. This gives opportunities to get a good grasp of the principles of control and the skills required to design simple control loops. To have a full understanding of PID control it is necessary to consider both linear and nonlinear phenomena.

The experiments were designed to maximize system use and expose the user to important industrial and theoretical control issues. A graphical user interface allows the user to download pre-compiled controllers and to plot and tune parameters on the fly. The system also exposes students to haptics and Virtual Reality (VR) which augments the system features with a "coolness" factor which, we hope, will arouse curiosity and stimulate students to pursue a career in controls. This workbook gives a brief description of the system, the rationale for its design, and some views on the pedagogy.

1.2. The Laptop Process

A photograph of the system (DCMCT) is shown in Figure 1.1.

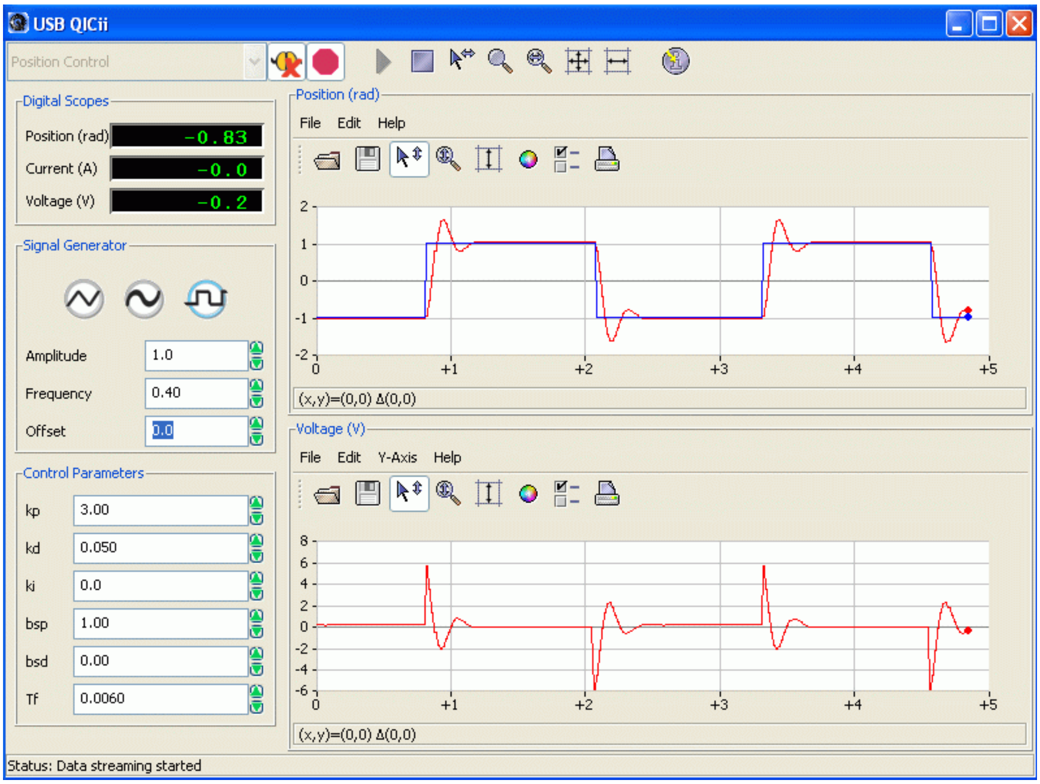
Figure 1.1 Photograph Of The QET DC Motor Control Trainer (DCMCT)

A complete description of the DCMCT is provided in Appendix A. The system consists of a motor instrumented with an encoder. The motor is driven using a linear power amplifier. The power to the system is delivered using a wall transformer. Signals to and from the system are available on a header as well as on standard connectors for control via a Hardware-In-the-Loop (HIL) board. The system may be controlled using an external PC equipped with a HIL board. Alternatively analog controllers can be implemented on the breadboard.

More to the point, a socket, which accommodates a PIC microcontroller, is also available. The PIC can measure the encoder, apply voltages to the motor amplifier, and communicate with a laptop using a USB cable.

In the context of this workbook, this system is used as a portable embedded control system which can readily be configured to perform control experiments using a laptop computer that communicates with the PIC microcontroller. The PIC microcontroller module, named QIC, plugs into a custom socket on the DCMCT board.

A software package, called USB QICii (please refer to Appendix B), that runs on the laptop allows one to download pre-compiled code to the PIC which performs the actual real-time control. USB QICii communicates with the PIC in real-time allowing for parameter tuning on the fly and data collection and plotting. In the example illustrated in Figure 1.2, the system is running a PID position controller.



Position Control

Position (rad) -0.83
Current (A) -0.0
Voltage (V) -0.2

Amplitude 1.0
Frequency 0.40
Offset 0.0

kp 3.00
kd 0.050
ki 0.0
bsp 1.00
bsd 0.00
Tf 0.0060

Status: Data streaming started

Figure 1.2 Screen Capture Of The QICii Software

1.3. The Method

The system can be used in many different ways. A detailed curriculum has been developed to guide students and teachers. The curriculum demonstrates the relevant characteristics of each control topic.

A systematic approach to performing the laboratories was designed. Each laboratory has a pre-lab preparation section in which the student performs all the theoretical developments required for the session and performs calculations for parameters which are subsequently used during the experiments. This ensures that the student is ready for the lab.

The pre-lab activity is followed by an in-lab activity where students do the actual experiments in a lab (or at home or in a coffee house). To do the lab the student simply launches the USB QICii application. A screen capture of a typical USB QICii session is shown in Figure 1.2. The manuals direct the student to perform specific experiments using the interactive software. Data is collected by the student for very specific activities and entered into pre-formatted tables. The tables facilitate the comparison of results obtained from theoretical derivations and actual performance. The student is then asked to discuss the results.

1.3.1. The Experiments

Many different experiments can be performed with the system. The following experiments were designed to entice the student into further examining control system design and to consider it as part of their future engineering expeditions.

1.3.1.1. Modelling

Although practicing industrial control engineers do not typically derive models of the system, they are controlling (the authors have seen heuristic manual tuning performed in some of the most demanding applications). This experiment stresses the importance of "**knowing the system before you control it**". This is also necessary to have a broader understanding of control. The students derive the theoretical open-loop model of the system and assess its performance limitations. The system is designed in such a way that a good model can be derived from first principles. The physical parameters can all be determined by simple experiments. Using QICii and the QET, the students perform experiments with its inputs and observe its outputs. Real-time open-loop tests are performed and system parameters are estimated using static and dynamic measurements. A first-order simulation of the derived model is run in real-time in parallel with the actual system and a bumptest is performed to assess the validity of the estimated model.

1.3.1.2. Speed Control

The PI controller is perhaps the most commonly used controller. Both students and practitioners of control should be well familiar with it. Speed control of a motor is a good way to learn PI control. Students are asked to investigate the qualitative properties of proportional and integral action to develop a good intuitive feel for PI control. Controllers are tuned both by empirical methods of the Ziegler-Nichols type and by design to given specifications. The student analyzes and tests the effect of set-point weighting. This is unfortunately often ignored in educational settings but relied on heavily in industrial control. The effect of integrator windup is examined and an integrator anti-windup scheme is tuned and evaluated. This is also a good way to demonstrate that performance can be drastically improved by introducing nonlinearities. Disturbance effects, simulated via a direct manual interaction or by a user switch activated by the QIC, are examined and steady-state errors due to triangular inputs are assessed. Tracking of square wave, sinusoidal, and triangular signals can be discussed.

1.3.1.3. Robustness

Robustness to modelling errors is an essential property of a good control system. Following the speed control experiment, the student is introduced to sensitivity analysis and stability margins. Sensitivity and complementary sensitivity functions for the speed control system are derived and the student is guided in designing a more robust controller than the previous one. Sampling delays and filtering effects are taken into account and the stability gain and phase margins are derived. The margins are then measured using the actual system. The QICii software allows the user to introduce sample delays in the loop as well as alter the loop gain. Using these features, the system can be driven to instability and the actual phase and gain margins can be obtained and compared with the theoretically derived values. Disturbance response is also assessed in light of the robustness concepts.

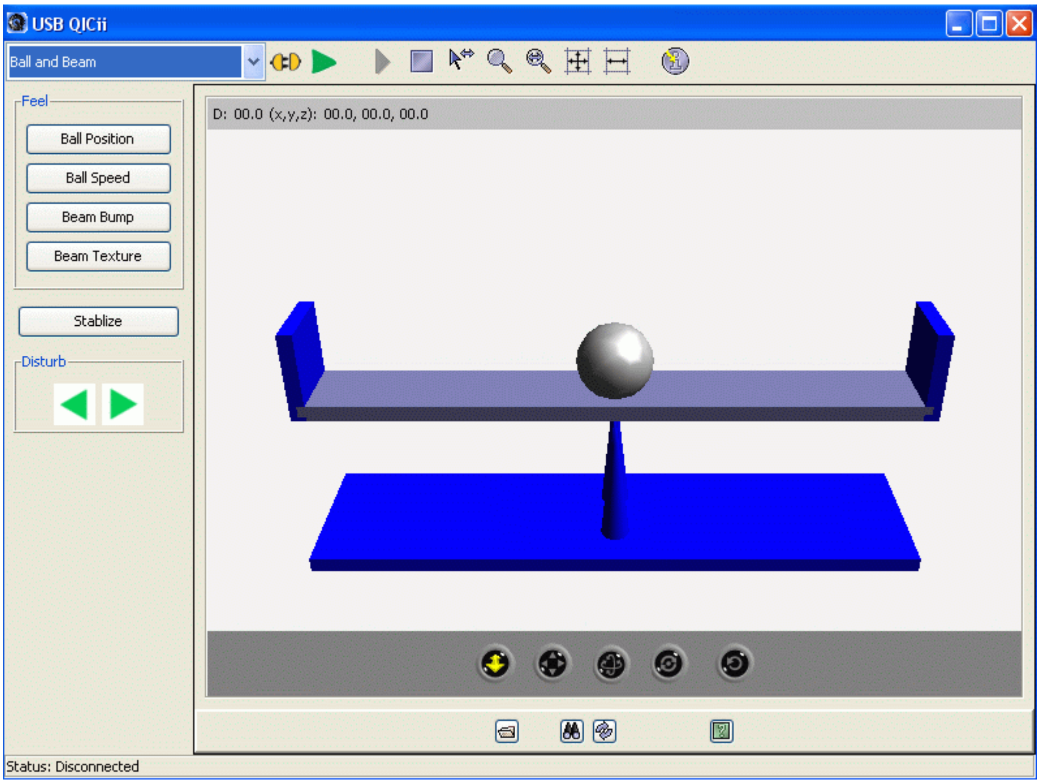
1.3.1.4. Position Control

Control of motor position is a natural way to introduce the benefits of derivative action. The student is asked to design a PID controller to specifications and analyze its response to step inputs, triangular inputs, and disturbances. The controller is implemented in the QIC module and the user assesses the effects of the three gains on system performance. With derivative action, the effect of measurement noise is also clearly visible. This gives a nice way to introduce noise filtering. Disturbance response is evaluated with and without integral control. Response to triangular inputs is also assessed.

1.3.1.5. Haptic Interaction

To illustrate that control is much more than the servo and regulation problem, we have also included some elementary haptics experiments. The student is introduced to impedance control using a feedback system. The joint stiffness and damping are derived using a position PD controller. It is shown that a haptic knob can be simulated by combining a PID position controller with a finite-state machine. The student can define detents and step sizes on the motor shaft. The motor shaft behaves as though it is a notched knob using software running on the QIC only.

The effectiveness of haptics in manual control is also illustrated by a second haptics experiment. The motor shaft is used as an input device to control a virtual ball and beam setup. The virtual ball and beam system is graphically animated on the laptop computer in real-time as shown in Figure 1.3.



D: 00.0 (x,y,z): 00.0, 00.0, 00.0

Status: Disconnected

Figure 1.3 Screen Capture Of The Haptic Ball And Beam System

In the virtual ball and beam experiment, the DCMCT motor shaft is used to command the beam angle. Ball dynamics are simulated in real-time on the laptop. Force feedback is used to feed different signals back to the shaft. The user can select to feel a variety of effects such as ball speed, ball position, and beam texture from the simulation via the motor shaft. The graphics representation is in three Dimensions (3D) and runs in real-time. The student is asked to assess whether it is easier to balance the ball on the beam using haptic feedback. Analysis on the potential pitfalls is requested.

1.3.2. CAD Files

All the calculations and equations derived in this workbook, and more particularly in the pre-lab assignments, are carried out in Maple worksheets supplied on the accompanying

CD. Using Maple 8 or later, a worksheet can be edited or re-configured by the instructor and the equations automatically re-derived, accordingly, by Maple.

Some of the pre-lab assignments in the Robustness Chapter require the writing of MATLAB scripts. The solution files to these assignments are also supplied on the accompanying CD.

1.3.3. Chapter Structure

1.3.3.1. Pre-Laboratory Assignments

The pre-laboratory assignments must be performed by every student before they go to the laboratory session and run the actual laboratory.

1.3.3.2. Solutions And Typical Results

Regarding the Gray Boxes:

The gray boxes present in the **instructor manual** are not intended for the students as they provide solutions to the pre-lab assignments and contain typical experimental results from the laboratory procedure.

1.3.3.3. Marking Scheme

A marking scale is used at the end of each question to evaluate the student performance. The evaluation scale is described in Table 1.1 and should be ticked by the instructor when marking.

Marking Scale	*Designation*	*Description*
0	Poor	Most answers and/or experimental results are wrong.
1	Average	About half of the answers and/or results are correct.
2	Excellent	Most answers and/or experimental results are correct.

0	1	2

Table 1.1 Marking Scale Description

1.3.3.4. Results Summary Tables

Every laboratory contains two results summary tables that should be completed by the students.

The first table is called the *Pre-Laboratory Assignment Results* table. It should be completed after all the pre-lab assignments are done. Please refer to the table of interest to resolve the pre-laboratory Section pertinent to the results.

⚠ *Note:*
The Teaching Assistant or Laboratory Supervisor should ensure that the table has been properly and fully completed before the student is allowed to perform the actual experiment. If the table is not completed, then the student cannot perform the experiment successfully. Information from this table is required to perform the experiment.

The second table is called the *In-Laboratory Results* table. It should be completed **during the in-laboratory session**. This table will assist the student in keeping track of their results in a concise manner. The table is used to compare theoretical parameters and results with experimentally obtained values.

⚠ *Note:*
The Teaching Assistant or Laboratory Supervisor should ensure that the table has been properly and fully completed before the student leaves the in-laboratory session.

Both tables are useful for quick and easy assessment of the work performed by the student. Of course honesty is assumed.

1.4. Curriculum Summary And Scheduling

The DCMCT system does not require the space and expense typically required for undergraduate control laboratories. The experiment can be signed out by a student and taken anywhere he or she wishes to perform the required experiment, at anytime (even on an evening).

The teaching material presented in this workbook can be divided into manageable two- to three- hour work periods, each of which covering one of the pre-laboratory or experimental sessions. One possible teaching outline is described in Table 1.2.

Session Name	*Pre-Lab Section(s)*	*In-Lab Section(s)*	*Laboratory Topics*
Modelling 1	2.5.1 - 2.5.2	2.6.2	Motor Static Relations Motor Parameter Estimation
Modelling 2	2.5.3	2.6.3	Dynamic Modelling: Bumptest Model Fitting
Speed 1	3.5.1	3.6.1 – 3.6.5	Qualitative Properties Of PI Control Ziegler-Nichols Tuning Method Set-Point Weighting PI Controller Design To Specifications
Speed 2	3.5.2 – 3.5.4	3.6.6 – 3.6.8	Integrator Windup Protection Tracking Ramp Signals Response To Load Disturbances
Robustness	4.5.2 – 4.5.3	4.6.2	Sensitivity Complementary Sensitivity Nyquist Diagram Stability Margins
Position 1	5.5.1 – 5.5.3	5.6.2 – 5.6.3	PD Position vs. PI Speed Controls System Achievable Performance Qualitative Properties Of PD Control PD Controller Design To Specifications
Position 2	5.5.4 – 5.5.5	5.6.4 – 5.6.5	Tracking Ramp Signals Response To Load Disturbances
Haptics	6.4.1	6.5.3 – 6.5.5	Impedance Control Haptic Knob Haptic Ball And Beam

Table 1.2 Laboratory Curriculum

As far as scheduling is concerned, you may either assign in-laboratory sessions, or alternatively, let the student sign out the system for a 24-hour period. This should suffice to complete the work described in one row of Table 1.2. In doing so, one QET-DCMCT system can be used by one student every day. Therefore, to run one row of Table 1.2 per week with a class of 40 students, the instructor will need 40/5 = 8 QET-DCMCT units.

Alternatively, if the instructor leaves one lab open for 8 hours every day and schedules two-hour sessions for each in-lab exercise, one DCMCT system can be used by 4*5 = 20 students (or groups) per week. Having 8 QET-DCMCT units set up in the lab results then in 160 students per week.

1.5. System Requirements

The laboratories described in this workbook are performed using the QET DCMCT module equipped with a USB QIC board and the USB QICii (QIC interactive interface) software. A full description of the system is provided in Appendices A and B.

1.6. References

[1] Bristol, E.H. (1986) An industrial point of view on control teaching and theory. IEEE Control Systems Magazine, 1986, 6:1: pp 24—27.

[2] Kheir, N.A., Åström, K.J., Auslander, D., Cheok, K.C., Franklin G.F., Masten, M., and Rabins, M. (1996) Control Systems Engineering Education, Automatica, 1996, 32:2, pp 147—166.

[3] Murray, R.M., Åström, K.J., Boyd, S.P., Brockett, R.W., and Stein, G. Future directions in control in an information rich world. IEEE Control Systems Magazine, 2003, 23:2: pp 20—33.

[4] Murray, R.W. (editor) Control in an Information Rich World. Report of the Panel on Future Directions in Control, Dynamics and Systems. SIAM 2003.

[5] Åström, K.J. and Östberg, A.-B. (1986) A teaching laboratory for process control, IEEE Control Systems Magazine, 1986, 6:5: pp 37—42.

[6] Åström, K.J. and Lundh, M. (1992) Lund Control Program Combines Theory with Hands-On Experience, IEEE Control Systems Magazine, 12:3, pp 22—30.