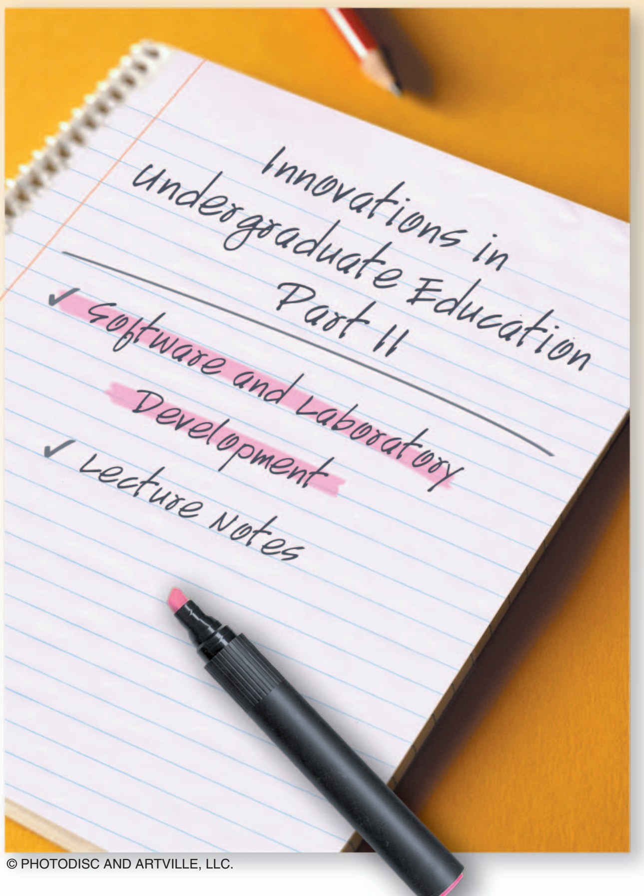
Integrating Experimentation into Control Courses

Hands-on experiments provide a stimulating educational environment



By René van de Molengraft, Maarten Steinbuch, and Bram de Kraker

A goal of the Department of Mechanical Engineering at the Technische Universiteit Eindhoven (TU/e), The Netherlands, is to provide a stimulating educational environment that emphasizes the role of hands-on experiments. The underlying pedagogical goal is threefold: 1) to apply newly obtained knowledge to help the students assimilate what they have learned, 2) to develop an attitude that values experimentation as an important and natural part of solving technical problems, and 3) to develop good experimental skills. As a result, the educational process becomes more attractive and meaningful to the students. Experimentation is widely accepted as an important part of the educational process [1].

In our view, this goal can be achieved by integrating an experimentation program with courses in the mechanical engineering bachelors curriculum, starting in the first year and gradually building in complexity through the third year. The main difficulty in implementing this idea is the large number of students involved, namely, 150 first-year students and 100 second- and third-year students. To make it possible for these students to perform experiments, we introduced a new approach, including a personal notebook, a set of 30 portable data-acquisition devices, a varied set of small-scale systems, and MATLAB-based software. An essential requirement for the new infrastructure is that it should be portable. Students can plan, prepare, and analyze the experiments on their own notebook computers wherever they wish. At present, 30 pairs of students can perform experiments simultaneously at arbitrary locations.

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This article discusses the most significant innovations in three of the systems and control courses, namely, signal analysis (first year, 150 students), positioning system (second year, 100 students), and Pizzabot Contest (third year, 25 students). In the first year, simplified devices are used to illustrate the behavior of models familiar to the students. In the second year, more realistic devices are offered, focusing on the integration of knowledge from various disciplines. In the third year, real-life devices are used to enable the students to understand the problems of industrial operation.

A current trend in control education is to set up virtual laboratories to perform experiments using the Internet [2]. Although this approach is useful, it is not our choice. We believe that students should be able to touch and feel the hardware. Discovering for themselves the influence of stiffness (P) or damping (D) in a controlled mechanical system is an experience students never forget. With the addition of integrating action (I), the system seems to come alive!

Infrastructure

Since 1998, every TU/e student has been provided with a high-end notebook computer. Our approach is to use the notebook as the control center for experiments, that is, for acquiring data, for driving actuators, and as a real-time controller, all covering the frequency range of interest from dc to 1 kHz. Today's notebooks are capable of performing such experiments in real time. Additionally, the infrastructure must provide the following facilities: 1) a compact and versatile real-time data acquisition device that can interface between the notebook and the subject device, 2) process devices to be used in the courses, and 3) software to control the experiments. These items are discussed in the following sections.

TUeDACS QAD Device

In our view, an interface between the notebook and the subject devices must be sufficiently compact to be portable, be provided with an integrated connector panel, be versatile, providing all the types of I/O ports needed for the experiments, must operate in real time without internal buffering of data, and must provide a fast link to the notebook. When we began this work three years ago, there was no commercial interface that fulfilled all of these needs, so we developed a new interface called QAD in cooperation with the TUeDACS group at TU/e [3]. The QAD has two analog input ports, two analog output ports, two 32-bit incremental quadrature input ports, and one 8-bit digital I/O port. This set of I/O ports enables a wide range of experiments to be performed. Currently, we have 30 QADs available within the department.

Practical Devices

Three simple practical hardware devices have been designed; there are 15 of each: a flexible shaft system, a leaf spring system, and a passive electronic filter. Other, more complex, hardware devices, including 35 ink jet plotters and four Pizzabots, were acquired from industry. These systems are used beginning in the second year.

MATLAB-Based Software

In our systems and control courses, MATLAB is the standard tool. Two applications, QadScope and Wintarget [4], have been developed for this environment. QadScope (Figure 1) is an oscilloscope-like user interface for measurement and open-loop control. Wintarget is a real-time target running under Simulink/Real-Time Workshop. With Wintarget, a real-time application (RTA) for use with the QAD can be built from the Simulink model by pressing a single button, allowing students to concentrate fully on controller design without being distracted by software implementation issues. The Microsoft Windows operating system enables us to achieve a mean jitter (the deviation in the sampling interval) of typically 0.2% for a 1 kHz sampling rate and an acceptable level for educational purposes.

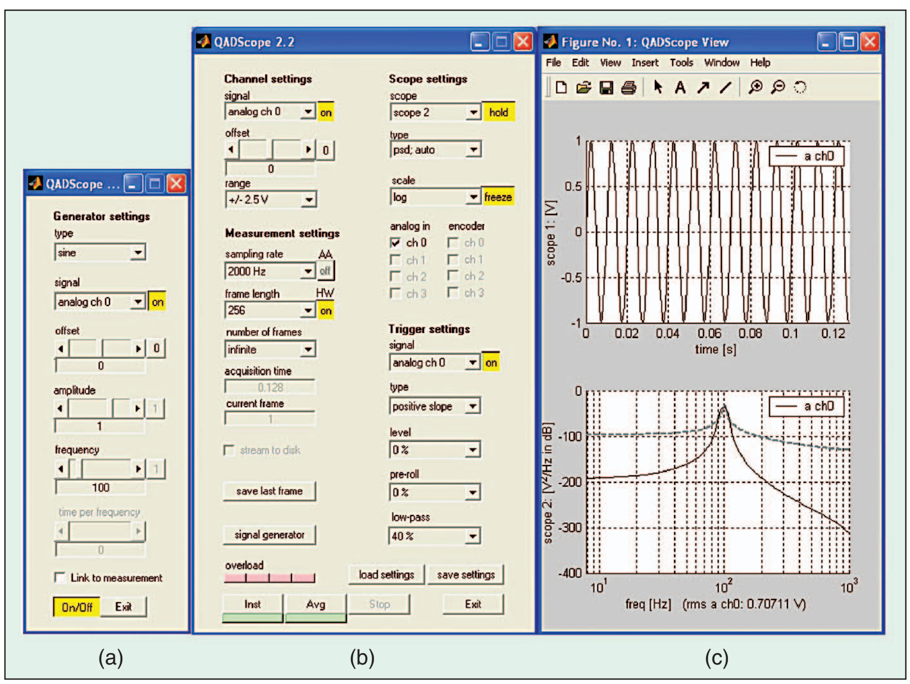

Figure 1. *QadScope measurement application. The (a) signal generator, (b) measurement settings, and (c) oscilloscope views facilitate a wide range of experiments.*

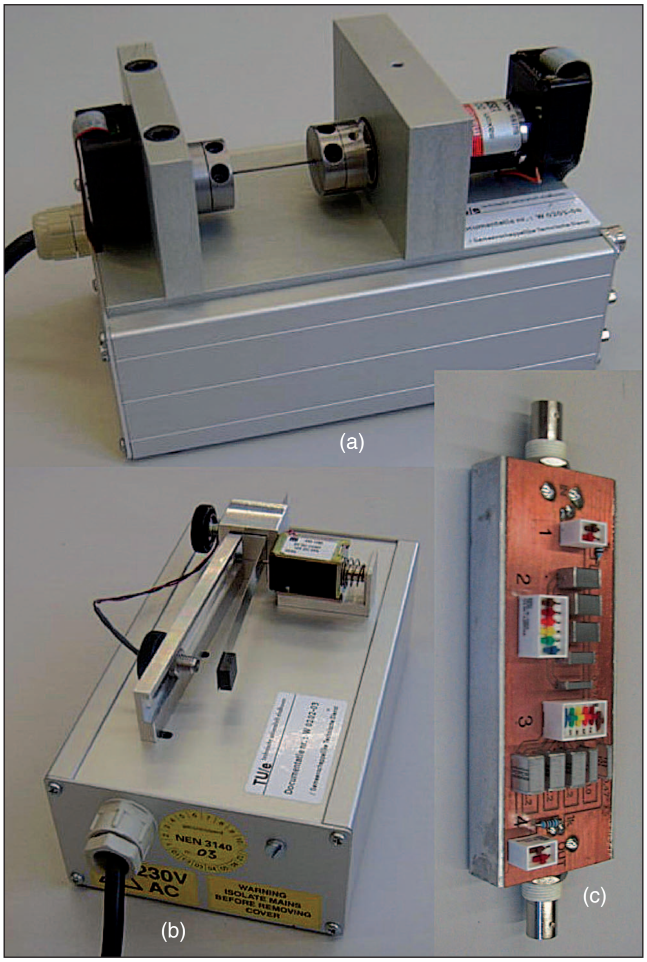

Figure 2. *Signal analysis devices. The (a) flexible shaft system, (b) leaf-spring system, and (c) passive electronic filter are portable devices for classroom or home use.*

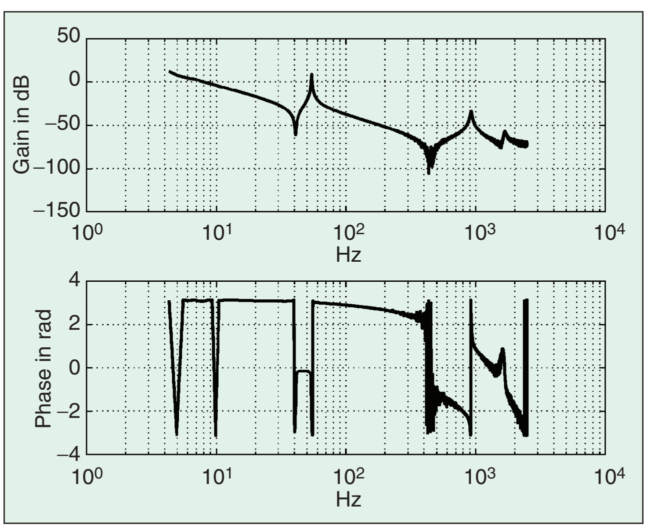

Figure 3. *Frequency response function of the fourth-order motion system. The antiresonances (zeros) and resonances (poles) are clearly visible. Up to a frequency of 200 Hz, the system can be regarded as a two-mass-spring system.*

Examples

This section describes three of the systems and control courses illustrating the gradually increasing complexity of the subject devices that students encounter.

Signal Analysis

Signal analysis, which is the first course in the curriculum, covers Fourier series, the Fourier transform, sampling, the discrete Fourier transform, and the Laplace transform. The course emphasizes practical aspects of the theory, such as analog-digital and digital-analog conversion (DAC), aliasing, windowing, and signal leakage. These issues are inevitably encountered as soon as signal acquisition and frequency domain analysis have to be performed in a real-life situation. During the lectures, demonstrations are given in advance of guided self-study sessions. The students are given a tutorial that leads them through the experiments, describing the actions to be performed in each step. One of the devices used in this course is the flexible shaft system shown in Figure 2. The system has a built-in servo-amplifier, and thus the DAC output voltage of the QAD can be used to drive the motor. The angular positions of both motor and load mass are measured by incremental encoders, and the quadrature inputs of the QAD are used to count the encoder pulses.

Figure 3 shows the frequency response function, representing the transfer function from the input voltage, which is proportional to the motor torque, to the angular position of the motor mass. This figure shows the double integrator character for low frequencies. In the measured frequency range, we can see three zero-pole pairs representing the antiresonances and resonances of the mechanical system. The first of these, at 40 Hz, is due to the low stiffness of the thin shaft, which connects the motor mass and the load mass. Exercises performed with this device include the following:

- Determine the relation between motor voltage and speed in stationary operation.
- Excite the motor with band-limited noise, and study the power spectral density of the motion response.
- Excite the motor at the first antiresonance frequency, which allows students to see the physical meaning of zeros in the transfer function.

Positioning System

The positioning system case study is the first situation in which the students deal with the control of a real motion system, in this case an ink jet printer (Figure 4). The students work in groups of eight, as in all design-centered learning cases in the second year. Twelve printers are available in our simulation and experimentation laboratory (SEL). The students have to design a feedback controller to control the position of the print head. The head is driven by a dc motor through a belt transmission, and the position of the head is measured by means of a linear encoder strip. Again, the QAD is the link between the notebook and the subject device. The students start by modeling the printer dynamics as a single-input, single-output (SISO) system. They attempt to match time and frequency response data obtained experimentally with simple theoretical models, including those for friction. Next, by making use of loop shaping in the frequency domain, the students design linear feedback controllers. The stability of the closed-loop system is analyzed, and the performance of the system is evaluated.

Controllers are designed in MATLAB/Simulink. The RTA is built with the use of Real-Time Workshop and Wintarget. After the RTA has been started, Simulink can be linked to the RTA using the external mode feature of Simulink. In this way, control parameters can be tuned from Simulink, and control variables can be traced, for example, by using Simulink scope blocks.

The project is completed with a poster, an oral presentation, and a discussion. Theory from various courses such as control engineering, signal analysis, and system analysis is applied directly to the case study. Students are motivated to see that the real-life performance of the apparatus can be controlled and understood.

Pizzabot Contest

In the Pizzabot Contest case study, six groups of four students compete to move three pizzas from one rack to another in the shortest possible time using the Pizzabot transposer robot (Figure 5). The Pizzabot is a four-axis robot, previously used in an LCD factory of Philips Electronics. The axis positions are measured by means of incremental encoders and driven by dc motors in combination with servo-amplifiers. Two QADs are used to operate one Pizzabot. The students have to develop their own plan of action and must operate as a professional project team to perform the following tasks:

- Model the Pizzabot based on experimentally obtained time and frequency response data for each axis and obtain a time-domain model of the friction.
- Define requirements for moving the pizzas as quickly as possible.
- Design feedback controllers by means of loop shaping, where the robot is assumed to behave as four decoupled SISO systems. Stability margins are monitored during the control tuning process.
- Design feedforward controllers based on rigid body models with dry friction, viscous friction, and gravity.
- Specify motion profiles. Most groups split the task into a large number of point-to-point movements using third-order set-point profiles.
- Evaluate the closed-loop performance in the time domain. If the requirements are not met, the control design must be reviewed.

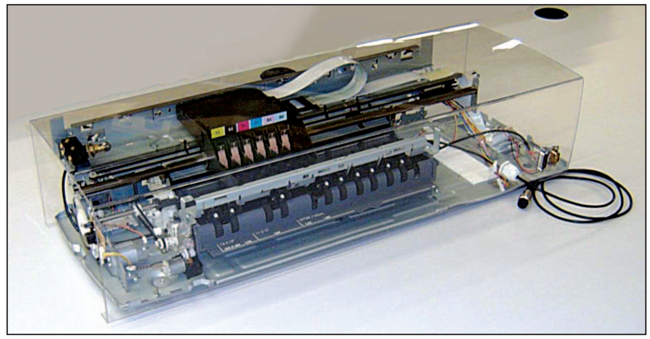

Figure 4. *HP ink jet printer as used in the second-year case study. A transparent hood with integrated connector panel has been added for safety and to allow students to observe the operation of the device.*

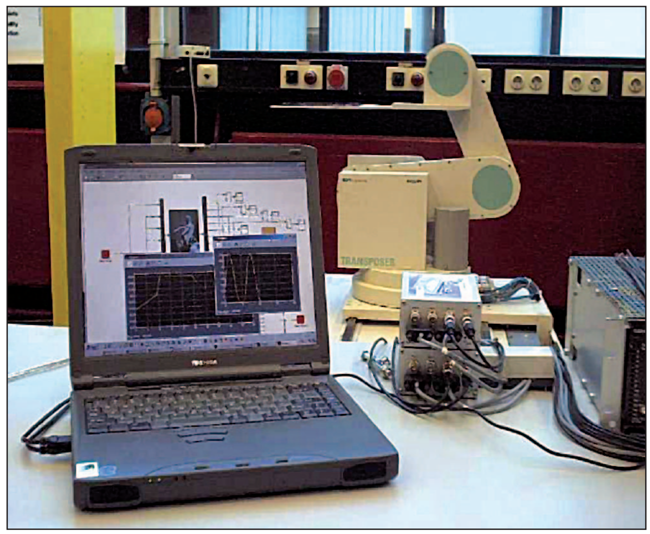

Figure 5. *The Pizzabot used in the third-year case study. Two QADs are used to operate the four robot axes, with the notebook acting as the real-time controller.*

To complete the project, a show is organized around the contest, and each group demonstrates their controller. The total time taken for completing the task is measured. A forum of staff members questions the students about their design choices and selects the winner.

Dealing with an industrial robot system presents a real challenge to the students in deciding which aspects of the robot's behavior are critical for controller design. Students particularly like the multidisciplinary character of the course and feel that they learn a lot by integrating their knowledge into a single design. The students also learn that performing the right experiment at the right time speeds up the design process tremendously.

Evaluation

Our approach to control experiments provides a unique opportunity to achieve department-wide integration of practical training in the curriculum. The approach is flexible and enables large groups of students to carry out experiments. Using detailed student questionnaires, the signal analysis course has been evaluated over the last two years. Students are enthusiastic about the guided self-study sessions with practical experiments. They believe that do-it-yourself experiments help them to absorb the material from the lectures, which satisfies the first part of our pedagogical goal. Initially, the students lack hands-on experience with this kind of equipment, but after getting used to our new infrastructure, they are eager to continue using it. We have observed that students consider the combination of notebook and QAD to be the standard equipment for performing experiments. Students know how to work with the notebook, and, on their own initiative, have started using it for other courses as well. Not only have students developed better experimental skills, they also show an increased awareness of the power of experimentation, and are able to invent new experiments for the problem at hand. Evidently, our pedagogical goal has been largely achieved.

Lessons Learned

For a successful large-scale implementation of experimentation throughout the curriculum, we need many devices, and they must be portable. The student notebook is a crucial factor, in that students can prepare and analyze experiments anywhere, anytime, and interactive courses with embedded experiments can be organized in almost every classroom and lab. Hands-on experience and experimentation contribute to developing an eager attitude among the students. Curiosity and creativity of the students are stimulated by our approach.

The systematic increase in complexity from simplified devices to real-world industrial systems helps students to develop modeling skills. In the first year, students recognize the basic models in the physical layout of the devices. In the second year, the more realistic devices appeal to the students' increased abstraction capability. In the third year, the industrial devices challenge the students to develop and validate different models for the purpose of analysis and design.

The combination of notebook, QAD, MATLAB/Simulink/RTW, and Wintarget effectively creates a rapid control prototyping (RCP) environment, in which students can focus on control design rather than implementation. For our mechanical engineering students, and probably for many others, having an RCP environment available is a prerequisite for real-time control experimentation during bachelors study.

In each study year, the new generation of notebook computers can create different conditions for our infrastructure. These conditions might involve a change in configuration such as new chipsets and buses, a new version of Windows, or a new version of MATLAB. As a result, maintenance of the infrastructure requires a substantial yearly effort. To obtain more control over some of these issues, we are currently in the process of migrating to a real-time Linux-based software environment that can be booted from a Linux Live cd-rom.

Our new infrastructure has broken through the practical barriers to large-scale experimenting for our students. The success of a further integration of student experimentation into the mechanical engineering curriculum depends largely on the efforts and creativity of staff members. It appears that the Control Systems Technology group has initiated a domino effect, and we have great hopes that this effect will continue in the years to come.

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