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Integrating Experiments in Control Education

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***Abstract*— This paper describes the process of renewing the role and educational setup of do-it-yourself experiments within the Bachelor and Master program of the Faculty of Mechanical Engineering at TU/e. In particular, the courses in systems and control are considered. A new infrastructure for performing experiments has been realized with two main features. Firstly, the infrastructure allows for letting large numbers of students perform experiments simultaneously at an arbitrary location. Secondly, hardware setups were developed that allow for a gradual increase in complexity from simple to real-life industrial systems.**

I. INTRODUCTION

The faculty of Mechanical Engineering (ME) at the TU/e (Eindhoven, The Netherlands) aims at increasing the role of experimenting in the ME curriculum and at the same time to integrate them in a challenging new educational environment. The purpose of this is twofold. Firstly, if students can directly apply newly obtained knowledge in practical cases, this will help assimilating what has been learned. Secondly, we are convinced that education will become more attractive to the students. Experimentation is widely accepted as an important part of education, see e.g. [1], [2], [3], [4], [5], [6]. During the past three years, experimenting has been integrated in several of the courses of the Control Systems Technology group of ME. The experience gained in these courses will be used in the near future to boost the practical component in other courses of the ME curriculum, too.

In the ME undergraduate curriculum, several main lines of topics can be distinguished. One of them is the Systems and Control (S&C) line of courses (in chronological order, trimester x.y meaning trimester y of year x):

- course Signal Analysis (trimester 1.2): Fourier analysis, sampling
- course System Analysis (trimester 1.3): linear dynamic systems, Laplace analysis
- course Control Engineering (trimester 2.2): frequency-domain based design of PID-type controllers
- course Positioning System (trimester 2.2): practical case, control of an inkjet printer
- course Multivariable Control (trimester 3.1): control of MIMO linear dynamic systems
- course Pizzabot Contest (trimester 3.3): practical case, control of an industrial robot

This paper will discuss the changes made in three of the S&C line of courses: Signal Analysis (150 students), Positioning System (100 students) and Pizzabot Contest (25 students). In the first year, the practical setups offered to the students are more or less *ideal*, very much representing te behavior of the simple models students are familiar with. In the second year, *realistic* though still fairly simple setups are offered, challenging students to integrate knowledge from various courses. In the third year, *complex* realistic setups are offered, showing the problems of real industrial applications. In the examples of this paper this gradually increasing complexity in the practical setups will clearly show.

Until now, experiments had to be carried out in faculty laboratories with the mechanical system at hand, measurement tools like oscilloscopes and a desktop computer for taking in data. This situation exists in many educational institutes, see e.g. the Dynamic and Control courses of Mechanical Engineering at MIT [7]. In order to be able to let large groups of students in the Bachelor phase perform experiments in classroom situations, a completely new infrastructure had to be built up. This infrastructure consists of a student notebook, a portable data-acquisition device (called QAD), a varied set of small-scale systems and Matlab-based software for experimenting. This infrastructure will be discussed in section II.

The current trend in control education is to setup virtual labs or doing experiments via the internet [8], [6]. Though this can be useful, it is not the approach we take. We are convinced that students should be able to "touch and feel" the hardware. Really feeling the influence of stiffness (P) or damping (D) in a controlled mechanical system is something students will never forget. Integrating action (I) even feels like the system starts to live!

A special feature of our approach is that the new infrastructure is not tied to a fixed location. Not only can students prepare and analyse the experiments on their own notebook computer anywhere they like, many of the practical setups themselves are highly portable, too. At the moment, we can let 30 groups of two students simultaneously perform experiments at an arbitrary location, even at home.

After the new infrastructure has been described in Section II, the three example courses will be discussed in Section III, followed by an evaluation of our experience and that of the students in Section IV.

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II. INFRASTRUCTURE

Since 1998, every new student at the TU/e receives a high-end notebook computer, which has become an essential assistant in many parts of the ME curriculum: professional tools, such as the general computing tool Matlab, the Finite Element program Marc/Mentat and the CAD/CAM tool Unigraphix, are intensively used right from the start.

For our purpose, the idea is to use the notebook as the centre for experimenting, i.e. the notebook acquires measurement data, drives actuators and acts as a real-time controller. Today's notebooks are capable of performing real-time tasks at fairly high sampling rates. The interesting range of frequencies for the experiments planned in the ME Bachelor is from DC to 1 kHz. Even under operating systems like Win2K, sampling rates of about 2 kHz can be realized in user mode with fairly good jitter properties.

To facilitate experimenting by the students in large groups we had to add basically three things:

- A compact and versatile real-time data acquisition device that can interface between the notebook and the practical setup.
- Practical setups to be used in the courses.
- Software to control the experiments.

These items will be discussed below.

A. TUeDACS QAD Device

For the experiments it is necessary to have an interface between the notebook and the physical setup. In our view this interface must fulfill the following requirements:

- It must be compact for portability, with integrated connector panel
- It must be versatile, so commonly used input/output (io) ports in ME experiments must be present.
- It must operate in real-time, i.e. no internal buffering of data is allowed.
- It must have a fast link to the notebook.

Three years ago when we started this work no commercially available interface was available that fulfills all our needs. So, we defined a new interface together with the TUeDACS group at TU/e ([9]). The TUeDACS group has further designed and built the interface, named QAD (see Fig. 1). The QAD has two analog input ports, two analog output ports, two 32-bit incremental quadrature input ports and one 8-bit digital io-port. This set of io-ports enables a wide range of experiments to be performed. An internal clock can generate interrupts to the notebook at arbitrary rates up to 100 kHz. The QAD has a 20 Mbit proprietary serial link to the notebook via a PCMCIA card. As many notebooks offer two PCMCIA slots, two QAD's can be used simultaneously by one notebook. Currently, we have 30 QAD's available within our faculty.

Fig. 1. TUeDACS QAD

B. Practical Setups

The laboratory of the CST group has available a number of industrial motion systems for use in research and education. Availability of these systems to students for the purpose of experimenting in courses is restricted. Furthermore, these systems are often too complex to be used by first or second year undergraduate students. Therefore we have developed a set of three simple practical hardware setups to be used in classroom situations:

- 4Th order motion system (Figs. 2 and 3)
- Leaf spring system (Fig. 4)
- Passive electronic filter (Fig. 5)

We have built 15 pieces of each type to be able to use them in larger groups of students. Other more complex hardware setups were acquired from industry for the purpose of experimenting in our courses, e.g. the inkjet plotters (35 pieces) and the so-called Pizzabots (4 pieces) (Figs. 6 and 7). These systems are used from the second year on.

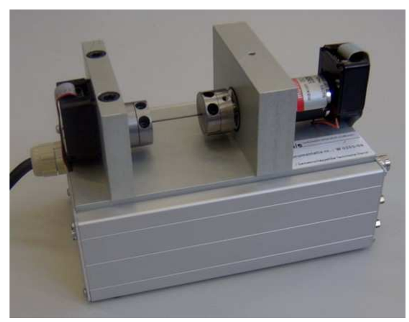

Fig. 2. 4Th order motion system as used in various S&C courses

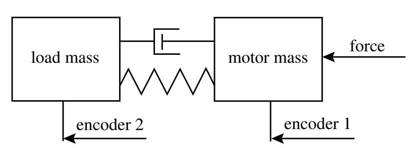

Fig. 3. Schematic of the 4th order motion system

C. Matlab-based Software

ME students are trained to use modern computing tools right from the start of their studies. For the purpose of the system and control courses, Matlab is the de facto standard tool. During the first year, students already develop programming and numerical analysis skills with Matlab via

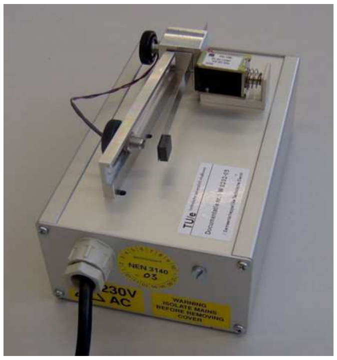

Fig. 4. Leaf spring system as used in first year's course Signal Analysis

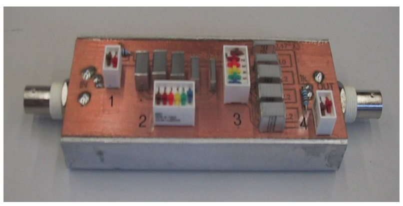

Fig. 5. Passive electronic filter as used in first year's course Signal Analysis

Fig. 6. Inkjet printer as used in second year's practical case

Fig. 7. Pizzabot as used in third year's practical case

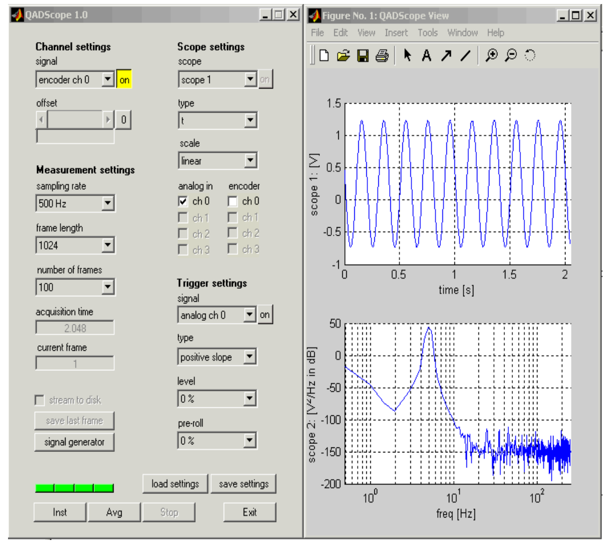

Fig. 8. QadScope main panel

the web-based Interactive Matlab Course (IMC) [10], also developed at TU/e. Two Matlab-based applications have been developed to be used in the experiments with the notebook/QAD combo: QadScope and Wintarget. QadScope is a scope-like user interface to be used for measuring and open-loop control. Fig. 8 shows the main program panel. For instance, in the Signal Analysis course Qadscope is the central operation panel for all experiments. Students do not have to worry about programming. They can focus on how the various sampling and triggering parameters should be set, not on how to program a measuring application. Wintarget is a real-time target to be used under Simulink/Real-Time Workshop. With Wintarget, real-time applications (RTA's) to be used with the QAD can be built from Simulink models by pressing a single button. In this way, students can fully focus on e.g. controller design and are completely shielded from practical implementation issues. In the first and second year of the study, this is an advantage, because students have only limited knowledge. In the third year, students should learn that at least some knowledge of the Simulink→RTW→RTA process is required.

Microsoft Windows is the operating system installed on all student notebooks. To obtain (soft) real-time behavior of user-mode programs under MS Windows, a timer driver has been developed. The mean jitter (deviation of sampling interval) achieved in this way is typically 0.2% for a 1 kHz sampling rate, which we consider to be quite acceptable for educational purposes.

The cost of developing and manufacturing all 30 QAD interfaces is 55 k euro. The cost of developing and building the 3*15 small hardware setups is 45 k euro. The student notebooks are paid for half by the university and half by the students themselves.

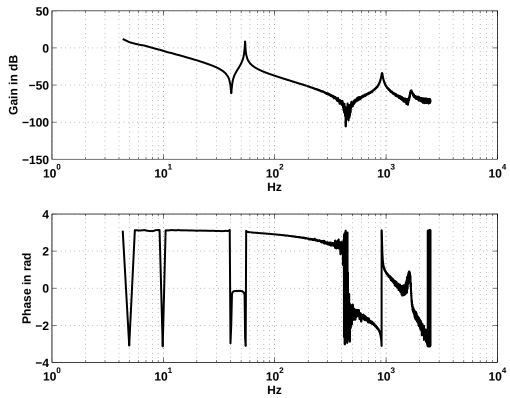

Fig. 9. Frequency response function of 4th order motion system

Fig. 10. View on workplace in Simulation and Experimentation Laboratory

III. EXAMPLES

In this section, three of the S&C line of courses are discussed that exploit the new infrastructure for experimenting. These courses also show the gradual increase of complexity in the hardware setups that students have to deal with.

A. Signal Analysis

The course Signal Analysis is the first S&C course in the curriculum. The course treats the following subjects: Fourier series, Fourier transform, sampling, discrete Fourier transform, and Laplace transform. Throughout the course, practical aspects of the theory are emphasized, e.g. analog-digital and digital-analog conversion, 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. Therefore, we consider it to be very important to provide our students with experimental skills. During the lectures, many demonstrations are given in advance of the guided selfstudy sessions, where students perform experiments themselves. For these experiments, a tutorial is given to the students that will lead them along the experiments, describing step-by-step what actions need to be performed. One of the setups being used in this course is the 4th order motion system as shown in Fig. 2. The system has a built-in 1.3 A servo-amplifier. The DAC-output voltage of the QAD can thus be used to drive the motor. The angular positions of both motor and load mass are measured by incremental encoders. The quadrature inputs of the QAD can be used to count the encoder pulses. The dynamic phenomena in this apparently simple systems are also found in wide class of industrial motion systems [11]. Fig. 9 shows the frequency response function for this system, measured from the input voltage (proportional to motor torque) to the angular position of the mass at the motor side. This figure clearly shows the double integrator character for low frequencies. In the frequency range measured, we already see three zero-pole pairs coming along, representing the antiresonances and resonances of the mechanical system. The lower one is due to the low stiffness of the transmission (thin bar) between the motor mass and the load mass. Examples of exercises performed with this setup are:

- Determine the relation between motor voltage and speed under stationary operation.
- Excite the motor with band-limited noise and study the power spectral density of the motion response.
- Excite the motor in its first antiresonance frequency. It is probably the first time our students see the physical meaning of a zero in the transfer function.

All of these experiments are controlled from within the QadScope program. During the experiments, students apply their new knowledge on signal analysis. At the same time, they see the use of that knowledge, which encourages them to study. Furthermore, aspects from other courses, such as the Dynamics course running in the same trimester, are already being integrated with this course, e.g. the (anti)resonance phenomena. Up to a frequency of 200 Hz the 4th order setup behaves nearly as the 2-mass-spring model that is extensively discussed in the Dynamics course.

The guided selfstudy sessions are held in 60-person classrooms. The rooms should have enough wall outlets for power supply (30 couples will need 90 outlets). By now, most classrooms at TU/e are well-equipped in this respect. Though network/internet access is not a prerequisite for experimenting, it is very convenient for distributing electronic manuals and software or for getting in contact with the lecturer. Since the arrival of the student notebook, all rooms at TU/e have network access.

B. Positioning System

The course Positioning System is a practical case study where students for the first time in their study deal with the control of a real motion system, in this case an inkjet printer. Students are working in groups of eight. 12 Hardware setups as in Fig. 6 are available in our Simulation and Experimentation Laboratory (SEL) (Fig. 10). In this course, students have to design a feedback controller for the position control of the printhead. The head is driven via a belt transmission by a dc-motor and its position is measured via

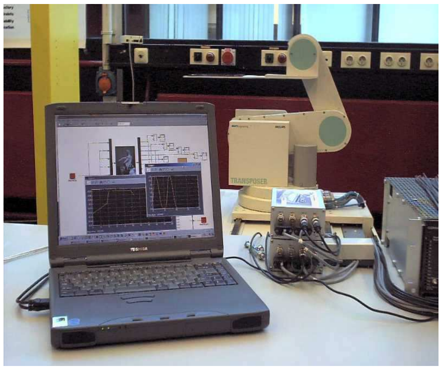

Fig. 11. Notebook with two QAD's operate a 4-axes Pizzabot

Fig. 12. Winners of the Pizzabot Contest 2001

a linear encoder strip. Again, the QAD is the link between notebook and printer. Students start by modelling the printer dynamics as a SISO system. Simple theoretical models (including those for friction!) and experimentally obtained time and frequency response data are tried to be matched. Based on this, linear feedback controllers are designed by means of loopshaping in the frequency domain. Stability of the closed-loop system is analyzed and performance is evaluated.

Controllers are designed in Matlab/Simulink. Via Real-Time Workshop and Wintarget the RTA is build. After the RTA has been started, Simulink can be linked to the RTA by means of so-called External Mode. Then, a TCP/IP link between Simulink and RTA is created over which data can be exchanged: in this way, parameters in the RTA can be tuned from Simulink and variables in the RTA can be traced, e.g. by means of Simulink scope blocks. As a consequence, many students initially do not see the difference between a simulation and a real-time experiment: in the Simulink environment both look quite the same!

At the end of the course, students present their work via a poster and an oral presentation to their fellow students. Theory from the Control Engineering course that runs in the same trimester is directly applied in this practical case. Knowledge of the previous courses Signal Analysis and System Analysis is essential for a successfull completion of the case study. It really motivates students to see that, using prior knowledge, real-life performance of the apparatus can be controlled and understood.

C. Pizzabot Contest

The course Pizza Contest is a practical case study where six groups of four students compete to bring three pizza's from one rack to the other in the shortest possible time, using the so-called Pizzabot (Fig. 7) as transposer robot. The pizzabot is a 4-axis robot. The axis positions are measured via incremental encoders. The axes are driven by dc-motors in combination with servo-amplifiers. Two QAD's are needed to operate one setup. The students start to make up their own plan of working. Contrary to the practical cases in the second year, the smaller teams now really have to work as a project team of different specialists. For a successful completion of the project the following topics are likely to be dealt with (although students are not forced to follow a particular direction):

- Modelling of the Pizzabot. Most groups end up with experimentally obtained time and frequency response data of the separate robot axes together with simple time domain models for the friction.
- Definition of the requirements to perform the task of moving the pizza's as fast as possible.
- Feedback control design via loopshaping where the robot is assumed to behave as four decoupled SISO systems. Stability margins are monitored during the control tuning process.
- Feedforward control design based on simple rigid body models with dry friction, viscous friction and gravity.
- Setpoint design for the task at hand. Most groups split the task in a large number of point-to-point motions using third order setpoint profiles.
- Evaluation of the closed loop performance in the time domain. If the requirements are not met, the control design must be reviewed.

As last part of the course, a contest takes place. Every group gives a demonstration of the controller they have designed. Total time for the task is measured. After the demonstration, a forum of staff members questions the students about their design choices. Finally, the forum points out the winner.

Again, controllers are designed in Matlab/Simulink. A high level Simulink s-function block is provided to the students to guarantee safe operation of the robot. Moreover, this block handles initialization and homing of the respective axes. In this way, even unstable controller designs will not physically harm the robot.

Dealing with an industrial robot system appears to be quite a challenge to the students. It is difficult for them to decide which aspects of the robot's behavior will be crucial for controller design. Students especially like the multidisciplinary character of the course. They feel that they really learn a lot by integrating all required knowledge in a single design. They also learn that performing the right experiments at the right time tremendously speeds up the design process.

IV. EVALUATION

The infrastructure that was built offers a unique opportunity to realize a faculty-wide integration of practical training in the curriculum. It is highly portable and suitable for experimenting in large groups.

The faculty of ME at the TU/e has a system of quality control in which course evaluations are based on student questionnaires. The course Signal Analysis has been surveyed twice during the last two years. Students acclaim the guided selfstudy sessions with practical experiments warmly. They believe that do-it-yourself experiments will help them in absorbing the material from the lectures. At the start, students have problems in mastering the entire practical setup as they lack experience with this kind of equipment. Once they see through it, they are eager to work with it. We have already observed that the experimental skills of the students have considerably increased in the past three years: as an example, after the new-style Signal Analysis course in the second trimester, the Strucural Dynamics project in the third trimester could address the student's new experimental skills showing more depth than in previous years. Also, we have observed that students consider the notebook/QAD combo the standard equipment for experimenting at ME: they know how to work with it and they have spontaneously started using it for other courses as well. Apparently, our new infrastructure has already taken down the "barrier" for experimenting, at least with regard to the students. The success of a further integration of experimenting in the ME curriculum largely depends on the efforts of fellow staff members. Within ME, the Control Systems Technology group seems to create a domino-effect, which will hopefully continue in the years to come.

Within the faculty of ME the CST group has a strong collaboration with the Dynamics and Control (D&C) group. At the moment, we are in the process of tuning the various courses to each other. The aspect of integrating experiments is part of the discussion.

Until now, the student notebooks have been provided with the various Microsoft Windows versions. About every year this version changes. This can imply a serious software development effort, for example the transition from Win9x to Win2K required development of both a new TUeDACS driver and a timer driver. Furthermore, as Windows is not a real-time os, real-time performance is restricted unless special extensions are developed to get round the imposed restrictions. In a closed environment like Windows this is not trivial. It seems therefore logical to switch to real-time (RTAI) Linux in the near future, as it is both real-time and open-source. Today's notebooks easily allow for a dual-boot setup. Furthermore, as notebooks will become more powerful, real-time performance is likely to increase.

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