Incorporating Hands-On Experiences in a First Course in Automatic Controls in the Information Age

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Abstract

First courses in automatic controls can incorporate hands-on experiences in the form of projects or formal laboratories so as to bring the lecture material to life. Such courses are typically offered at the senior level, where engineering students learn to combine and apply the modeling techniques, numerical methods, and other analytical skills they have learned in prior courses with basic control theory and tools in order to perform classical control tasks. Although having a fully equipped formal laboratory would be preferable for students to experience applying their controls skills, such facilities are not always available, or may be in the planning stages. This may be more common at smaller (but hopefully growing) and/or undergraduate-only engineering programs, where teaching is rightfully emphasized more than state-of-the-art controls research laboratories. Lean budgets can also delay planned implementation of controls teaching laboratories. Still, to get even a few hands-on experiences in a traditionally lecture-only first course in automatic controls would benefit students in several ways. First, the material in such a course can be fairly esoteric and/or outright boring to some students if not related to real-world applications, experienced firsthand. Hands-on experiences of any type tend to capture students' interest and imagination. Second, there is no substitute for being able to tweak a real-time controlled system and immediately observe the effects of parameter variation, model refinement, control law implementation issues, and even system crashes due to instability. Moreover, incorporating hands-on controls experiences with modern hardware and software (Quanser®, WinCon®) based on computer tools with which the students are already familiar (MS-Windows®, MATLAB®, Simulink®) can logically add to the value and freshness of students' education. Such initially implemented hands-on experiences, along with feedback from students, can form the precursor to implementing a future formal controls laboratory. This paper discusses the incorporation of such hands-on experiences into the senior level course in automatic controls at the University of Tennessee at Martin.

Introduction

The UT Martin Department of Engineering offers a Bachelor of Science in engineering degree with available specialties in mechanical, electrical, civil, and industrial engineering. A senior-level course in automatic controls, ENGR 462 Linear Controls System Design, is required for the mechanical and industrial specialties. Students specializing in electrical engineering may take ENGR 462 as an approved elective. The specific prerequisites for ENGR 462 are ENGR 241 Dynamics, and ENGR 316 Engineering Analysis II. The former is a traditional sophomore-level course in engineering dynamics and the latter is a second course (of a junior-level course pair, ENGR 315 & 316) in mathematical modeling and analysis of engineering systems. These prerequisite courses serve to equip students with the tools necessary to model dynamical systems and analyze system responses with Laplace transform and numerical methods, which are fundamental to the study of automatic controls. ENGR 462 is designed as a conventional, senior-level, 3-credit-hour lecture course on automatic linear controls. In this particular thread of courses, there are no laboratory experiences involving hardware directly associated with these courses. Students in all four specialties attend labs for related required courses, such as Circuits I, Vibrations, Instrumentation and Experimental Methods, and Electronics I. Thus, students are exposed to mechanical and

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electrical dynamical system modeling, and also thermal, fluid, and economic systems modeling in the required thermodynamics, fluid mechanics, and engineering economy core courses. Students learn about spring-mass-damper systems, RLC circuits, thermal systems, and devices suitable for actuators and sensors, but not at the level of integration of even a fundamental automatic control system, such as DC motor control or liquid-level height control. Mechanical, electrical, and industrial engineering specialty students need to experience control systems in action, and all engineering students need a firm understanding of feedback as a concept, so why not drive home the concept with exercises that all engineering students may experience? Plett and Schmidt [1] describe a multidisciplinary controls laboratory, include some student feedback, and note that some students try some experiments that are not even assigned; such is their level of interest. Other interdisciplinary undergraduate controls labs are described by Johnson et al. [2], and Melendez-Gonzalez and Beauchamp-Baez [3]. It would be advantageous for students to get hands-on experience in automatic controls to enhance their understanding of the subject, particularly those students whose learning is especially facilitated by laboratory experiences, and for all students in general. Schmitt [4] describes a controls laboratory that serves several engineering departments within a college of engineering, thus facilitating an interdisciplinary approach to controls education and research. Bernstein [5] declares that the implementation of even simple control systems enhances learning, and that even demonstration labs have some educational value. The author, as the faculty member responsible for teaching the controls course at UT Martin, decided to incorporate two fundamental DC motor control experiments into the course as a pilot effort. The issues of a full-blown laboratory section, budgeting, scheduling, and resultant curriculum revisions did not need treating. Harrison [6] describes a mechatronics course in which students perform hands-on exercises as interdisciplinary teams without dedicated laboratory time, with good results. Similarly good results were observed from this initial UT Martin effort.

Relation to Student Cognition Models and Why Controls Course Needs Such Augmentation

Felder [7] illustrates the sensor student learning type, contrasts it with the intuitor learning type, and points out that most undergraduate engineering students tend to exhibit primarily sensing traits. They may appreciate the theory, but as others have pointed out, there is no substitute for implementing a control system, having it work, and tweaking parameters in real-time to observe the effects on the system. Simulations can only get across so much information. When presented with the theoretical background of frequency domain-based controls, some students' eyes glaze over. Some confuse block diagrams with circuit diagrams. Some mix time and frequency variables together on a block diagram. The author recalls having had similar difficulties when seeing this material for the first time, too. If, however, the students can see which piece of hardware corresponds to which block on a block diagram, it helps them to appreciate the usefulness of block diagrams. If they can see all the control system design process stages of system modeling, response specification, control law selection, component selection, controller gain calculations, response simulation, preliminary system parameter tuning, and final implementation and tuning of a control system, then they can process what they have learned in the lecture and relate it to real-world applications. Even if all they experience is proportional-plus-derivative-plus-integral (PID) control laws, they are still better off than if they had experienced nothing in a concrete way, for they will have seen the fundamental theme of linear controls in action, namely, feedback control. Most of our students will never become controls engineers, but they will likely encounter PID controls in industry, particularly in manufacturing and processing industrial settings, where many of our graduates obtain employment. It would seem to be a reasonable thing for them to encounter implemented control systems first in an academic experimental setting. Lang, et al. [8] present the results of a formal survey of industrial engineering employers and relate them to the ABET EC-2000 Assessment criteria, including the result that experience in conducting experiments in general is of relatively high importance to industry. The course lecture also includes some elements of active and cooperative learning methods, which are discussed in the course description.

Course Description

The course is described in the syllabus as an interdisciplinary approach to analog and digital feedback control system design for integrated systems. The course includes block diagrams, transfer functions, state equations, stability, steady state error, time response, Bode design, root locus design, and design of lead/lag compensators and

PID controllers. Felder and Brent [9] give some specific insights as to how to consider the approach to the design of laboratory sections in light of the ABET EC-2000 Assessment Criteria, in addition to presenting a framework for putting in place elements likely to lead to a program's successful meeting of the criteria. One of the tools discussed are well-thought-out course instructional objectives. Some of the desired course instructional objectives for the students are listed in the syllabus as follows:

Upon completion of the course, students should be able to:

- Converse using basic vocabulary of linear controls engineering
- Distinguish between open loop and closed loop control
- Identify applications of open and closed loop control
- Derive and manipulate transfer functions of control system components
- Create, interpret, and manipulate control system block diagrams
- Determine a control system's response to various inputs with Laplace transform methods
- Specify desired system transient and steady state system responses to given inputs
- Perform transient and steady state response analysis of a system subject to a given input using transform methods
- Perform transient and steady state response analysis of a system subject to a given input using MATLAB®
- Tune a PID Controller
- Design and implement real-time controllers for real computer-controlled plants using state-of-the-art hardware and software

The students would need reasonable competencies in the listed learning objectives in order to be able to perform the hands-on experimental experiences. The first eight weeks serve to prepare the students to perform a first hands-on experience, and by the end of the tenth week, they have been exposed to the material required in order to perform a second experience. In order to perform the hands-on experiences, students require knowledge of system modeling, feedback, transfer functions, block diagrams and their reduction, simple control laws, and transient and steady state response specifications. Thus, the exercise experiences could not be performed until about mid-semester, with the first familiarization experience being performed in week eight. The first actual controls implementation experience was performed in weeks ten and eleven, immediately following the covering of transient response characteristics and specifications in the lecture. The course activities are weighted as follows:

- 20% Homework (about eight)
- 20% Exam I
- 20 % Exam II
- 20 % Hands-on Experiences (two)
- 20% Final Exam

A standard 10-point grading scheme is employed, and there is no curving of grades. The course is offered annually in the Fall, and meets Mondays, Wednesdays, and Fridays for 50-minute lecture periods. A fairly traditional lecture format is employed, with occasional small group-based active learning activities included. In such activities, students break into groups of two or three, and spend a few minutes outlining problem solutions and brainstorming lists of general answers and questions. The instructor then goes around the groups and solicits input, which is then put on the whiteboard, and the whole class discusses the results. Felder et al. [10] discuss the effectiveness of such methods in helping to stimulate and maintain students' interest in the lecture material. In response to the mid-term course assessment question "Do the short in-class small group activities help reinforce the material for you?" one student wrote, "I feel they do help. They make us think and work together." The incorporation of these techniques is new to the controls course and this is the first time the author has attempted to use such modern methods.

Overview of Experimental Experiences

The available experiments include state of the art modular linear and rotary plant-based systems by Quanser Consulting, which employ an MS-Windows®/MATLAB®/Simulink®/WinCon®-based programming environment. Dixon et al. [11] discuss MATLAB®-based controls tools and argue for their standardization. The capability to perform linear and rotary position and velocity control of DC-motor-driven plants is a basic one. More advanced capabilities include control of an inverted pendulum on a cart, a linear flexible joint, a linear flexible link, a rotary flexible joint, a ball-and-beam, and a single-story active mass damping. One computer, equipped with a data acquisition board, software, and power amplifier is available, so only one experiment may be performed at a time. Due to the small throughput in this initial offering of the hands-on experiences, this is not a drawback. The equipment is well documented, including thorough student procedure handouts that are made available to the students. The author finds the accompanying instructor handouts quite useful.

Students' Efforts and Experiences

The students performed the first two experiments in the rotary suite. The first is a "fire-familiarization" exercise in which the students become familiar with the rotary plant components, wiring up the system, and navigating the software. They learn how to drive the DC motor open loop and how to read the various feedback devices (potentiometer, encoder, and tachometer). They see how the software packages MATLAB®, Simulink®, and WinCon® work together in the MS-Windows® environment to get commands to and feedback from the plant. They turn in reports consisting of several short answer questions. In the next experiment, the students design a proportional plus velocity controller, which is essentially an easier-to-implement proportional plus derivative controller, for the rotary plant. The standard design goal of finding suitable proportional and derivative controller gains, given a maximum overshoot and peak time for a step input response is the theme of the experiment. The students have to incorporate the control law and open-loop plant model into a closed-loop system, form the closed-loop transfer function, put it in a standard form, obtain expressions for natural frequency and damping ratio based on the desired peak time and overshoot, and finally calculate a proportional and derivative gain. The experiment includes a Simulink® model of the system, and students experience the control task of simulating the system response with calculated values, seeing that they need to be tuned, and observing the effects of changing controller gains on the response. Upon satisfactory simulation of the controller, students implement the controller on the rotary plant. Again, they experience the iterative nature of control gain tuning. A report is generated by the students, in which they discuss their observations and answer specific questions about the experiment. One of the more important things to come out of the exercise is an appreciation by the students for the three stages of controller implementation: initial modeling and gain calculation, simulation and preliminary tuning, and implementation and final tuning. The instructor emphasizes the fact that the textbook methods and equations are applicable, but that the results need iterative improvement. The published parameters used in the modeling of the system are reasonably accurate to the point that not too much tuning is required. Indeed, acceptable performance is typically obtained by using the published parameter values as-is. The instructor made himself available to the students and made several trips down to the lab room where the equipment was located in order to answer questions and give hints and ask provocative questions of his own.

Students' Reactions

Students generally liked the experiences. Seeing the plant respond under a controller they designed and implemented was rewarding to them, after initial periods of frustration. One of the questions the students addressed in their reports concerns what the students think are good and maybe not-so-good aspects of the experiences from a learning standpoint. Some of the more interesting responses concerned not being able to directly get a natural frequency and damping ratio from the plot of the response easily. Greater emphasis on graphical methods in future offerings of the course should help the students with this. Some students commented on the issues of model parameter uncertainties affecting the calculated and simulated results as compared with the implemented controller response, which is a sure indication of light bulbs going on over students' heads.

Instructor's Observations

Students had typical problems with block diagram reduction, understanding the difference between simulation and implementation, and complained somewhat about having to use time outside the lecture, scheduled in concert with the instructor, to perform the experimental experiences. The instructor sympathized, but was able to get the point across that there was time overhead associated with homework, too, about which no one thought to complain.

Recommendations / Future Plans

The instructor plans to include linear plant experiments in future offerings of the course in addition to the rotary plant experiments. This could make for up to four hands-on experiences without a formal laboratory section. Future plans also include using one lecture period per experience to do a demonstration and walk-through with the students, instead of just going over the handout during lecture without the hardware. As experience is gained in evaluating the effectiveness of this method, the author plans to include the inverted pendulum on a cart as a capstone experience in the course. When the inverted pendulum was demonstrated on the first day of class, the students' imagination was quite obviously captured. To have students gain experience working with such a classical control system in a first course in automatic controls would be highly desirable.

Conclusions

A senior-level first course in automatic controls has been augmented with the incorporation of two state of the art commercially available controls experimental experiences without adding a formal laboratory section at the University of Tennessee at Martin. Students work in a semi-self-paced manner to perform the experiments, and report the results. The students report that the experimental experiences help them to better understand the lecture material. More and more challenging experiences are planned for future offerings of the course.

Acknowledgement

This project is funded under an agreement with the State of Tennessee, Department of Commerce and Insurance, Board of Architectural and Engineering Examiners.

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