An Interdisciplinary Control Systems Course for Engineering Technologists: Description of Lecture Topics and Laboratory Experiments

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Abstract

For the past two years we have offered a required senior-level control systems course with laboratory designed to be taken jointly by mechanical engineering technology (MET) and electronics engineering technology (EET) students. This course focuses on the interdisciplinary nature of control systems and represents a departure from the traditional approach of teaching a separate control systems course to each engineering technology discipline. Certain controls concepts, such as dynamics and modeling, frequency response, feedback, and stability, are of fundamental importance and usefulness in virtually all engineering technology disciplines. The coursework begins with basic concepts and terminology and moves through a set progressively more challenging control problems involving the key elements of servo control, PID control, process control, and data acquisition. Theory-reinforcing laboratory experiments include dc motor characterization and speed control, liquid level and flow control, and MATLAB / Simulink computer simulations to verify experimental data. Interdisciplinary teamwork is stressed by forming lab groups with two or three students, on which there must be at least one MET and one EET student. Throughout the course the students often act as mentors for each other in the lab, with MET students being better prepared to work on the process control experiments and the EET students being better prepared to work on the motor and motion control experiments. Student evaluations of the interdisciplinary course have been mixed, with some students expressing the desire for separate MET and EET courses, and other students expressing the desire for coursework that was narrower in scope and in more depth. The faculty believe the course is on track with the broader needs of industry today for engineering technologists with interdisciplinary skills to design, build, and maintain products requiring the integration of electronics, computer, and mechanical technologies.

Introduction

The restructuring of control systems education for senior-level engineering technology students at Cleveland State University began about three years ago. At that time, the only controls taught was in the servomechanism-oriented course EET 440 Feedback Control Systems and the associated lab course EET 441 Feedback Control Systems Laboratory. Both electrical engineering technology (EET) students and mechanical engineering technology (MET) students were required to jointly take the theory course (EET 440), but the MET students were exempted from taking the lab course (EET 441) because they lacked adequate "electrical" background to perform the lab experiments.

Clearly, it was thought, what the MET students needed was a controls course of their own, with a suitable laboratory component. As a result, two new courses were approved by the college faculty for the MET program: GET 430 Electrical Power, Controls, and Instrumentation; and, GET 431 Electrical Power, Controls, and Instrumentation Laboratory. Figure 1 shows the topics that were proposed by the MET faculty for the new courses.

electrical machines - 1 wk
power electronics & motor controls - 2 wk
feedback control circuits - 1 wk
electrical interfaces - 1 wk
actuators - 1 wk
sensors - 2 wk
data collection - 1 wk
PC interfaces and programming - 2 wk
PLC programming - 2 wks

Figure 1. Proposed topics for new controls course for MET students

As the courses were being developed (for first offering in Spring 2003), the EET faculty proposed a revision to the EET 440 / EET 441 course sequence in the EET program to bring them in line with the new course under development for the MET program. It was argued that, by its very nature, control systems is a multidisciplinary subject, and preparation for a career as an engineering technologist builds on an understanding of this inherently cross-disciplinary nature of systems and control principles. For example, certain controls concepts, such as dynamics and modeling, frequency response, feedback, and stability, are of fundamental importance and usefulness in both engineering technology disciplines.

The new course development effort then shifted to preparing an interdisciplinary course in control systems designed to be jointly taken by MET and EET students. The balance of this paper describes this effort, including the research done in preparing a final course outline and the work done to couple meaningful hands-on laboratory exercises with the theory topics. The research began with a brief search of the literature for previous work at developing interdisciplinary controls courses.

Literature Search

A complete review of control systems engineering education was made about ten years ago by Kheir, et al.[1] Sample programs relating to control from twelve universities, seven from the United States and five from Europe and Asia, were surveyed for the paper. Kheir reports that a first course in control frequently has students majoring in electrical, mechanical, aeronautical, or chemical engineering, which reflects on the interdisciplinary nature of the field. The subsequent more advanced courses tend to be less interdisciplinary, however, since engineers from the different classical disciplines approach the field of control differently, based on the science and technology of their discipline.

More recently, two interdisciplinary controls laboratory course developments have been described.[2,3] Practical experiments on control principles are described that have been devised for students of several disciplines. For example, experiments (servomechanisms) that use mechanical plants, electromechanical actuators and sensors, and electrical compensation are common for all disciplines. Some students will be more familiar with one part of the system than another, and the experience of working in a small team with students from another discipline can be very interesting and educational.

More pertinent to our theory-plus-laboratory course development efforts, however, is the report on the workshop sponsored by the National Science Foundation (NSF), the IEEE Control Systems Society (CSS), and other professional organizations on new directions in control engineering education.[4] The NSF/CSS workshop identified a road map for reform leading to significant changes in how control systems are taught in most universities. Controls has a number of elements common to all disciplines. Team work on the job suggests interdisciplinary training may be of value to students in preparation for the workplace. The ideal (recommended) approach is to provide controls training over the four-year college curriculum, which can be viewed as follows: (1) start with first year college students and provide practical experience in control systems that emphasizes fundamental principles; (2) develop new courses and materials that broaden the first-year experience, such that third-year engineering students should be introduced to system modeling, planning, design and simulation, system performance evaluation; (3) develop follow-up courses, for fourth-year engineering students and graduate students, that emphasize theory, digital control, real-time systems, nonlinear control, and other areas such as robotics, mechatronics, and manufacturing engineering.

At CSU in the Department of Engineering Technology, we don't have the usual four years in which to spread out the control system education. Our students come to CSU, having completed an Associate of Science degree, to complete years three and four of the bachelor's degree program in either mechanical engineering technology or electrical engineering technology. Curriculum constraints in each program allow for just a single senior-level course (with laboratory) in which to provide some fundamental control systems education. The course topics were organized with the NSF/CSS workshop recommendations in mind: (1) begin with topics that emphasize the basic principles of control systems; (2) then broaden the fundamental concepts by introducing control system modeling, design and simulation, and the evaluation of system performance; and, (3) finish with introductory coverage of topics in digital control and PLC sequential control.

Course Structure

The lecture course is designed to be completed during a 15-week semester, with two 1.25-hour meetings per week. The associated laboratory course is also designed to meet for 15 weeks, with two 1.25-hour meetings per week; each laboratory-course meeting immediately follows the lecture-course meeting. The lecture topics and laboratory exercises are organized throughout the semester to supplement each other and, together, provide the desired overall control systems education; see Table 1.

Table 1. Organization of Lecture Topics and Laboratory Exercises in 15-Week Semester

Wk	Lecture Topics	Laboratory Exercises
1	Basic concepts and terminology	Computer-based tools for control systems
2	Types of control; mathematical	Matlab (review of complex arithmetic)
3	foundations: Laplace transforms,	Maple (includes Laplace transform)
4	introduction to modeling system dynamics.	Simulink (DEQ models & simulation)

5	Dynamic responses, Bode plots, damping	DC motor control
6	Actuators: electric motors, modeling,	modeling, block diag, transfer function
7	transfer functions, and simulation	characterization (Ke, Kt, Ra, La)
8	Continuous process modes of control	open-loop speed control
9	Methods of analysis: Bode diagrams,	build motor drive (pwm)
10	stability gain and phase margins, root locus	closed-loop speed control (build cont)
11	Process models: flow, thermal, mechanical	closed-loop position control (Simulink)
12	Process variable actuators and sensors	Process control
13	(temperature, flow, pressure, level)	data acquisition
14	Digital control and control of discrete	liquid level control (on-off controller)
15	processes (PLCs)	flow control (digital controller)

Fundamental concepts in control systems are emphasized during approximately the first five weeks of the lecture course. Referring to the topic headings used in Table 1, the following comments list the important control concepts covered during the lecture periods for each topic.

- *Basic concepts and terminology* includes an introduction to block diagrams and transfer functions, open-loop and closed-loop control, load changes, damping and stability, objectives and criteria of good control, and block diagram simplification.
- *Types of control* provides overviews of analog and digital control, regulator and follow-up systems, process control, servomechanisms, and sequential control.
- *Mathematical foundations* include the use of the Laplace transform to form transfer function models for dynamic systems described by differential equations and the use of computer software tools such as Matlab, Maple, and Simulink for solving controls problems.
- *Dynamic responses* include step-response dynamic characteristics in the time and frequency domains, such as rise time, settling time, overshoot, damping, steady-state error, bandwidth, gain and phase diagrams (Bode plots).

The fundamental concepts are broadened during the next seven to eight weeks by introducing control system modeling, design and simulation, and the evaluation of system performance. Referring again to the topic headings used in Table 1, the following comments can be made.

- *Actuators* emphasizes the electric dc motor concepts: principle of operation, steady-state characteristics, dynamic model, transfer functions, and simulation using Matlab / Simulink.
- *Continuous process modes of control* covers two-position (on/off), P, I, PI, D, PD, PID control modes, electronic analog controllers, op amps and analog signal conditioning, solid-state switching components, and dc motor drives.
- *Methods of Analysis* includes Bode diagrams, stability, gain and phase margins, Nyquist stability criterion, and root locus.
- *Process models* covers the dynamics (DEQ) models of electrical, fluid flow, thermal, and mechanical systems.
- *Process variable actuators and sensors* include temperature, flow, pressure, liquid-level systems.

Advanced topics such as *digital control and control of discrete processes (PLCs)* are introduced during the last two weeks of the semester. Topics covered are digital signal conditioning (data acquisition, data sampling and conversion, D/A and A/D converters) and digital controllers (sampling, control algorithms, integral and derivative modes).

Laboratory Component

The laboratory course (GET 431 / EET 441) runs concurrent with the theory course (GET 430 / EET 440). The students meet first for lecture on theoretical concepts and then have a laboratory period in which they conduct practical experiments designed to reinforce and extend controls concepts. The theory and lab courses are purposely scheduled back-to-back to provide relevant hands-on exercises that immediately follow the theory presentation in lecture. This minimizes the amount of required pre-lab review material and also allows in some cases more advanced laboratory exercises.

The experiments are designed to give students the opportunity to compare real dynamic data with theoretical predictions, based on hand calculations and computer models developed using Matlab / Simulink controls software. Eleven experiments have been developed, which are organized to track the theory presented in the lectures and to provide an exposure to modeling and the cross-disciplinary aspects of control systems.

Experiment 1. Matlab: Introduction to basics, programming, and plotting. This lab teaches how to use Matlab to solve problems involving complex numbers, polynomials, and differential equations. This provides some mathematical foundations for control system analyses to be covered later in the course.

Experiment 2. Using MAPLE: Introduction to basics, programming, and plotting. This lab teaches how to use MAPLE to solve problems involving complex numbers, polynomials, differential equations, and the Laplace transformation. This provides students with another useful dynamic analysis software tool, plus more mathematical foundations for control system analyses to be covered later in the course.

Experiment 3. Using Simulink to Solve DEQs of Physical Systems: This lab teaches how to use Simulink to model dynamic systems and to simulate their response to control systems inputs such as the step, ramp, and sinewave. The dynamic systems (thermal, fluid, mechanical, and electrical) were chosen to reflect the interdisciplinary nature of control systems.

- Problem 1: Thermocouple temperature step response
- Problem 2: Tank liquid level response to pulse disturbance in inlet flow
- Problem 3: Mechanical spring-mass-damper motion step response
- Problem 4: Electrical LRC circuit current response to sinusoidal input
- Problem 5: Mechanical dynamic vibration absorber (damping a sinusoidal input)

Experiment 4. Electric DC Motor Modeling and Simulation: In this lab, students develop and validate a basic model for a permanent-magnet DC motor. They model the armature-voltage-controlled DC motor with differential equations and with the Laplace transform of the differential equations. The motor parameters from the manufacturer's data sheet are used to characterize the motor. A Simulink model is developed based on the motor differential equations and simulations (solutions) are generated.

Experiment 5. DC Motor Characterization: Students determine three parameters used to analytically describe the operation of a fixed-field DC motor – armature resistance, R_a ; torque constant, K_T ; and armature inductance, L_a . Locked-rotor tests are run to determine motor armature resistance and torque constant. A step-response test is made (with the rotor locked) to determine the motor armature electrical time constant, from which the armature inductance may be determined. These parameters are used in a Simulink model to simulate the motor operation and response to input armature voltage and different load torques.

Experiment 6. DC Motor Open-Loop Speed Response: Students develop static and dynamic models for a dc motor. They build a motor drive circuit and pulse-width-modulated (pwm) control controller. Then students measure the open-loop (uncontrolled) steady-state speed-torque characteristics and dynamic speed response of a DC motor, using a coupled DC generator as a tachometer for speed measurement. They develop and run a Simulink model to simulate the motor steady-state and dynamic speed (step) responses, and compare the results with the experimental data.

Experiment 7. DC Motor Closed-Loop Speed Control: Students build an analog controller using op amps for dc motor closed-loop speed control. A DC generator-tachometer is used to develop a feedback signal, which is proportional to the motor speed. Controller settings are adjusted and the motor speed step response is then measured and plotted. Two different controllers are studied: a proportional (P) controller, and a proportional-plus-integral (PI) controller. After the experiments, a Simulink model for each of the two controllers is run, using the controller setting(s) determined during the experiments. The theoretical and experimental data are compared.

Experiment 8. DC Motor Closed-Loop Position Control: A computer study of a position control system is made. Using Simulink, a motor position closed-loop control system is simulated and the position controller is designed theoretically using the computer. The controller settings are adjusted and then the motor position step response is simulated and plotted. Three different controllers are studied: a proportional (P) controller; a proportional-plus-integral (PI) controller; and a proportional-plus-integral-plus-derivative (PID) controller.

Experiment 9. Digital Control, Data Acquisition, and Instrumentation: In this lab, process control trainers are used that feature a liquid flow system, with a control valve powered by an electrically-controlled actuator, and with pressure and flow transmitters, all connected to a PC (computer)-based data acquisition system. The physical system and the associated data acquisition system are studied and described in the student lab report. Process variables are measured and recorded at a series of valve positions. Transient responses in flow and pressure to steps movements of valve position are recorded.

Experiment 10. Liquid Level Control and Fluid System Modeling: Students investigate two different control schemes for establishing and maintaining liquid level: (1) two-position (on-off) control; and, (2) indirect control using a calibrated flow control scheme.

Experiment 11. Flow Control Using Discrete (Digital) Controllers: Students investigate discrete (digital) control schemes for establishing and maintaining the liquid flow, using software control algorithms. They implement the following control functions and study the effectiveness of each in the control of fluid flow: (1) proportional (P) control; (2) proportional-plus-integral (PI) control; and, (3) proportional-plus-integral-plus-derivative (PID) control. They also develop a Simulink model for the CPC liquid-flow system and obtain plots of the flow versus time in response to step changes in the flow reference.

Interdisciplinary teamwork is stressed by forming lab groups with two or three students, on which there must be at least one MET and one EET student. Throughout the course the students often act as mentors for each other in the lab, with MET students being better prepared to work on the process control experiments and the EET students being better prepared to work on the motor and motion control experiments.

Course Evaluation

Student evaluations of the interdisciplinary course have been mixed, with some students expressing the desire for separate MET and EET courses, and other students expressing the desire for coursework that was narrower in scope and in more depth. The faculty believe the course is on track with the broader needs of industry today for engineering technologists with interdisciplinary skills to design, build, and maintain products requiring the integration of electronics, computer, and mechanical technologies.

Summary

This paper describes the development work of an interdisciplinary course in control systems designed to be taken jointly by mechanical engineering technology (MET) and electronics engineering technology (EET) students. This course focuses on the interdisciplinary nature of control systems and represents a departure from the traditional approach of teaching a separate control systems course to each engineering technology discipline. Certain controls concepts, such as dynamics and modeling, frequency response, feedback, and stability, are of fundamental importance and usefulness in virtually all engineering technology disciplines. The course topics were organized based on recommendations in a report on the NSF/CSS workshop on new directions in control system education; the coursework was organized as follows: (1) begin with topics that emphasize the basic principles of control systems; (2) then broaden the fundamental concepts by introducing control system modeling, design and simulation, and the evaluation of system performance; and, (3) finish with introductory coverage of topics in digital control and PLC sequential control. The laboratory experiments, which reinforce and extend the lecture topics, include dc motor characterization and speed control, liquid level and flow control, and MATLAB / Simulink computer simulations to verify experimental data. Interdisciplinary teamwork is stressed by forming lab groups with two or three students, on which there must be at least one MET and one EET student.

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Biography:

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