Providing Hands-on Experiences in a Mechanical Engineering Controls Systems Course

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Abstract:

As is the case with many Mechanical Engineering (ME) curricula, undergraduate ME students at Ohio Northern University (ONU) are required to take a Control Systems course. The typical student at ONU will take this course (ME 419) during the winter quarter of their senior year. After teaching this course for the first time in the winter of 2001, it was felt that a significant improvement could be made to the laboratory portion of this course. With the assistance of an ONU Faculty Development Grant and colleagues Dr. Hurtig (Assistant Dean and Assistant Professor of Electrical Engineering) and Dr. Rider (Professor of Mechanical Engineering), Dr. Yoder completely revised the laboratory schedule for the 2002-2003 academic year. The course changes and assessment of the results will be discussed, as well as plans for future improvement of the course laboratory experience.

Introduction:

Controls Systems is a course in which students often feel a disconnect between the mathematics they see during analysis and any real application of the theory (course evaluation comments from the 2001-02 academic year agreed with this general trend). Mechanical Engineers have little experience relating Laplace-space or Frequency-space equations to physical systems. The benefits to student learning of hands-on experiences and design experiences have been well documented [1-3]. Such work is strongly encouraged by the ONU Engineering Strategic Plan which states “A balance of 'hands-on' applications and theoretical expertise and understanding should be established in order to best prepare the students for future professional endeavors [4].” ABET also continues to stress the ability to design systems and conduct experiments as important criteria [5]. The authors sought to improve student learning and student interest in this course (as well as this field of study) by allowing students to experiment with simple, working, control systems, and to design controllers for a specific, desired response.

While most ME curricula do include a course in classical control theory, far fewer include a laboratory experience as part of this course. Several papers have been published describing interdisciplinary laboratories related to controls [6-9], but few are specific to a mechanical engineering controls course. Some of the programs that do include a lab (either in a required course or as an elective) can be found at [10-13].

The Change:

It is standard practice in the T.J. Smull College of Engineering at Ohio Northern University for every course to have published course outcomes that are used for assessment. For ME 419, these outcomes state that upon completion of this course, the student will be able to:

1. Draw and simplify block diagrams.
2. Use Laplace Transforms to solve differential equations.
3. Model real-world systems using Laplace Transforms, block diagrams, and Matlab.
4. Design digital control systems using digital logic or PLC programming.
5. Analyze control systems based on steady-state error, disturbance rejection, feedback, transient response, and stability.
6. Design a controller, selecting appropriate gains for a specified response.
7. Use the root-locus method.
8. Use frequency-response methods (NOTE: This outcome was not included in the 2001-2002 academic year)

The laboratory portion of the course should be designed to provide support and measure some or all of these course outcomes. In the 2001-2002 academic year, the following laboratory exercises were completed during the quarter (the number indicates which week the lab was performed):

1. Simple Digital Logic tutorial (hands on using Digiac boards)
2. Design and prototype a 4-switch combination lock requiring a memory circuit (on a computer using simulation software).
3. Use Matlab for system modeling. Start with problems from textbook as examples, then move to a more complicated problem involving a PID controller. Look at the effects of the three gains in the PID loop.
4. Using a system described by a visiting controls engineer, model feedback, disturbances, and uncertainties using Matlab.
5. Using a simple mass-spring-damper, students are asked to show cases where the following are true, and to find cases where they are not:
    a. Feedback reduces sensitivity
    b. Feedback improves transient response
    c. Feedback improves the response to disturbances
    d. Feedback improves steady-state error.
6. Simulate and design controllers for second order systems.
7. Examine placement of the poles and zeros, and introduction to Simulink.
8. Design a proportional controller for speed control of a motor with an unknown offset and gain in the power amplifier. Test the system using an actual motor.
9. PLC program design: Duplicate the functionality of the combination lock from Exercise 2.
10. Quiz/Review of other labs.

Table 1 relates these laboratories to the course outcomes. An X in a block indicates that the laboratory for the week is related to that course outcome. Course outcome 8 is marked with all asterisks because it was not an outcome for this year.

Table 1: Correlation of 2001-2002 laboratory relationships to course outcomes

		Course Outcomes							
		1	2	3	4	5	6	7	8
Week	1				X				*
	2				X				*
	3					X	X		*
	4	X		X		X	X		*
	5	X		X		X	X		*
	6	X		X		X	X		*
	7	X		X		X	X		*
	8	X		X		X	X	X	*
	9				X				*
	10	X		X	X	X	X	X	*

While the laboratory exercises did a good job of supporting course outcomes, note that only two of the laboratories required real, hands-on work (weeks 1 and 8). Week 9 did involve programming a PLC, but it did not interface with any physical devices. Several students commented on the fact that they appreciated the lab during week 8 because it brought things together and allowed them to see physically what had, to that point, only been seen through equations and simulations.

This provided the incentive to alter the laboratory portion of the course. During the summer of 2002, Dr. Yoder worked with Dr. Rider and Dr. Hurtig to modify the structure of the laboratory portion of the course. An agreement was created which allows the ME students and faculty to use laboratory space and equipment belonging to the Electrical and Computer Engineering and Computer Science (ECCS) Department. This allowed access to much more laboratory equipment without substantial cost.

Figure 1 : Students examine system wiring

Figure 2: Student enters PLC program

After these changes, the following laboratory schedule was followed for the 2002-2003 academic year:

1. Simple Digital Logic tutorial (hands on using Digiac boards).
2. Use a PLC to control the level of liquid in a tank. The PLC controls a pump and an alarm, allowing the user to select the level of liquid to maintain. Several digital switches are used to monitor the liquid level. Then, students were asked to design a digital circuit to complete the same task. The team with the cheapest circuit based on current chip prices received a bonus. Figure 1 shows students examining the system wiring so that they could create the ladder logic, and Figure 2 shows a student entering his program on the PLC.
3. This lab was completed using motor control systems owned by the ECCS department (commercially available systems from L.J. Technical Systems). These systems were used to do basic motor speed control and system identification. Students created a block diagram to model the system, and took measurements to determine the (steady-state) system parameters. They then changed gains and compared actual and calculated steady-state errors when the system was subjected to a disturbance (by applying a brake).

4. This was a modification of lab 5 from the previous year. The students used the model of the speed control system they had developed the previous week. Then, using Matlab to simulate that system, they were asked to show cases where the following statements are true, and cases which disprove these same statements:
    a. Feedback reduces sensitivity
    b. Feedback improves transient response
    c. Feedback improves the response to disturbances
    d. Feedback improves steady-state error.

    Then, using motor data from a standard catalog, they were asked to show what effect a different motor might have on the same control system. This was helpful for students to understand sensitivity.
5. This laboratory once again used the L.J. Technical System motor speed control systems. Students used oscilloscopes to monitor the systems' response to an input square wave, and were asked to determine the system parameters in order to model the motor as a standard first-order system. Using this data, along with the data from lab 3, they then compared measured performance of the system to calculated performance using hand calculations and Matlab simulations, for:
    a. Open loop systems with various proportional gains.
    b. Closed-loop systems with various proportional gains.
    c. Closed-loop systems with PID control.
6. This week's lab asked students to take a given second-order system, and control it. Students were not given the transfer function of the system. Rather, they were given the step response of the system (each student group was given a different response). Then, they were to determine the system transfer function, and design and test a controller in Matlab. They were asked to choose a controller (proportional-only) to create a critically-damped system, and then to design a proportional-only controller to achieve a given peak time and steady-state error. Finally, students we asked to improve the performance of their system using PID control.
7. Use a Labview VI to design a proportional controller for speed control of a motor with an unknown offset and gain in the power amplifier. Test the system with an actual motor. (This is lab 8 from the previous year.) Use Simulink to compare results of the actual system to simulation.
8. Add PID control to the system from lab 7. Use Root-locus to design a controller, then compare theoretical and actual results. Finally, as a bonus, use integration of the tachometer feedback to create a PID controller for position rather than velocity.
9. Again, the L.J. Technical systems were used to examine the frequency response of the systems. Bode plots were created, and the students were asked to find the transfer functions of the system by finding the gains and break frequencies.
10. Quiz/Review of other labs.

Table 2 shows the relationship between the new laboratories and the course outcomes for ME 419.

Table 2: Correlation of 2002-2003 laboratory exercises to course outcomes

		Course Outcomes							
		1	2	3	4	5	6	7	8
Week	1				X				
	2				X				
	3	X		X		X	X		
	4	X		X		X	X		
	5	X		X		X	X		
	6	X		X		X	X		
	7	X		X		X	X		
	8	X		X		X	X	X	
	9	X							X
	10	X		X	X	X	X	X	X

Results:

The first goal of this course modification was to allow students to have more hands-on experiences in the laboratory portion of the course. This was clearly achieved. Compared to the two hands-on laboratory sessions in 2001-2002, the new lab course gave students contact with physical systems in 7 of the ten weeks (all but weeks 4, 6, and 10). In addition, labs 4 and 6 built off of experiences they had with hands-on equipment (finding motor constants and controller gains for lab 4; finding system response to a step input for lab 6).

It is sometimes the case that providing students with hands-on experiences is seen as ‘fluff,’ in that it does not truly help in the educational process. It is possible, for example, that students could be more interested in the field of controls due to these labs, but learn less. In this course, it can be seen by examining the matrices relating course outcomes to laboratory content that the new laboratories all relate to as many (or more) course outcomes than did the previous laboratory exercises. The laboratories were designed specifically with the course outcomes and with the current course content in mind.

It is felt that this range of laboratory experiences provided the students with a much better understanding of control concepts. This is especially true of being able to better understand and visualize the basic parts of a typical block diagram (input, plant, disturbance, feedback, and output) and system performance characteristics (such as steady-state error, response time, and overshoot). This is evident in student performance on the laboratory reports and in the classroom, as the exam averages increased by over four percentage points. However, it was not seen in the student self-scoring on the achievement of course outcomes. Students are asked to score their achievement of each outcome ranging from 0 (not achieved at all) to 5 (achieved very well). The student self-scoring for each of the outcomes is given in Table 3.

Table 3: Annual student self-scoring averages of course outcomes

		COURSE OUTCOMES							
		1	2	3	4	5	6	7	8
YEAR	2001-02	4.1	3.9	3.8	3.8	3.9	3.7	3.4	*
	2002-03	4.3	3.6	3.2	3.8	3.7	3.7	3.1	3.4

As can be seen, only outcome 1 (block diagrams) showed improvement, with outcomes 2, 3, 5, and 7 dropping. The drop in outcome 3 (modeling real-world systems) is of particular concern, since it fell the furthest, and since several labs in the new course required them to do this, while only one lab did this during the 2001-02 class. Possible explanations for the outcomes dropping would include:

- Adding a week of lectures and a laboratory exercise on frequency response methods necessarily detracts from other topics. One would expect some drop in outcomes whenever additional material is added to a course.
- Students spend very little time in class regarding the use of Laplace Transforms. They are asked to work through a workbook on their own in order to be prepared for this. As such, the change in outcome 2 (modeling via Laplace Transforms) is likely unrelated to the changes made in the course.
- In some sense, exposing students to hands-on systems makes them realize the complexity of control systems. For example, consider the root-locus method. If, as was the case in the 2001-2002 class year, you only use this method as an abstract, mathematical tool, it may seem relatively simple to understand. One can use it to check for stability and to choose gains. However, in the 2002-2003 class year, students had to compare these theoretical, ideal values to actual gains which were used to control a physical system. This made them realize that there was far more involved in the system than the root-locus plot can tell them. Outcomes 3, 5, and 7 are all outcomes where students had this type of realization when working with a physical system. In some sense, then, this could be a case of "the more you learn, the less you know."
- The laboratory exercises are performed in groups, and reports are handed in as a group. It may be that while I did observe better results in the aggregate, some individual students did not get much from the laboratories.
- The course had nine more students in the second year, meaning more and larger lab groups, and less individual attention from the professor during the laboratory session.
- Finally, this standard assessment tool does not provide much information about the laboratory – it was developed for the course as a whole.

In order to get a better understanding of what individual students thought of individual laboratories, the survey on the following page was given to the students. The average value for each item is entered in the appropriate blank. Note that the results are based on a scale of 1-4. Questions that refer to the 'the lab upstairs' are indicating the laboratory exercises that utilized the L.J. Technical Systems motors from the ECCS department.

Winter Quarter, 2002-2003
ME419
Laboratory Evaluation:

Use the following scale

4 – Strongly Agree 3 – Agree 2 – Disagree 1 – Strongly Disagree

3.0 1) Using the DIGIACS helped my understanding of **digital logic**.

3.1 2) Using LOGICWORKS helped my understanding of **digital logic**.

3.4 3) The 'water level' lab helped my understanding of **PLCs**.

3.0 4) Using the speed control systems in the upstairs lab helped my understanding of **block diagrams.**

3.3 5) Using the speed control systems in the upstairs lab helped my understanding of **proportional gain**.

3.0 6) Using the speed control systems in the upstairs lab helped my understanding of **disturbances**.

3.1 7) Using the speed control systems in the upstairs lab helped my understanding of **feedback**.

3.1 8) Using the speed control systems in the upstairs lab helped my understanding of **first order systems**.

3.4 9) Using the speed control systems in the upstairs lab helped my understanding of **frequency response**.

3.4 10) I am comfortable using Matlab or Simulink to model systems.

3.0 11) I am comfortable using Matlab or Simulink to design a controller by varying gains and observing the response.

2.9 12) Implementing a proportional controller in Labview helped my understanding of control systems.

2.9 13) Implementing a PID controller in Labview helped my understanding of control systems.

I learned the most from the lab that: ________________________________

I learned the least from the lab that: ________________________________

This survey did seem to indicate that most students felt the laboratory work helped them understand basic concepts. Only one student strongly disagreed with more than one of the statements, and only three students (of thirty-five) strongly disagreed with any statement. The PLC laboratory and the frequency response laboratory, both hands-on labs, earned particularly high scores, as did using Matlab and Simulink to model a system (this last item is quite interesting, as it relates closely to course outcome 3, which received a particularly low score). Also, while the Labview labs (questions 12 and 13) received the lowest scores at 2.9, seven students listed these as the labs from which they learned the most.

Conclusions and Improvements:

Improved student learning was observed in the 2002-03 school year in the form of higher test scores and better laboratory reports. It is felt that this was partly due to the modified laboratory exercises that stressed hands-on experiences with control systems. However, student self-scoring of learning outcomes was lower in some cases. Various possible reasons for this have been presented.

In addition, a student self-scoring survey was completed relating to particular labs. On this survey, students did not single out a particular lab as ineffective, and generally agreed (or strongly agreed) that the laboratories did help their understanding of important concepts in control systems. Based on this, starting in the 2003-04 school year, the hands-on component of these laboratories will be kept, or possibly expanded. Special attention will be taken to make sure that students see the relationship between laboratories and course outcomes. Also, some lecture time will be devoted to explaining the differences between predicted, theoretical performance and actual, experimentally observed results.

Additional changes are being planned for this laboratory. Starting in the 2004-05 year, it is expected that this laboratory will be moved to a newly remodeled space. A proposal has been submitted to NSF that would allow the implementation of a new, interdisciplinary follow-up complex systems course. This course would provide additional equipment that could be used for additional hands-on experiments, likely in the fluids and/or heat transfer areas. The ECCS department has purchased new digital systems from Quanser, and ME 419 will likely begin using these systems for hands-on controls laboratory exercises in the 2004-05 year. These will be particularly beneficial since they allow control directly from Matlab or Simulink, allowing students to easily compare simulated and actual performance. It is hoped that assessment will show that these additional changes will continue to improve student learning and student achievement of course outcomes.

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Biography

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