Mini-Lab Projects in the Undergraduate Classical Controls Course

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Abstract:

To address a common complaint from students that the undergraduate controls lecture course in mechanical engineering is too abstract, an electromechanical mini-lab was developed. The term “mini-lab” is used here to emphasize the fact that the lab augments the lecture, but does not replace a full controls lab. This mini-lab consists of a simple DC motor and flywheel with either tachometer speed, or potentiometer position, feedback to implement speed or position control. The students were required to model the system, design controllers using root locus techniques, simulate the compensated system using MATLAB and Simulink, and implement their controllers using analog circuitry contained in a supplied breadboard kit. The students, placed into groups of three, then debuged and tested their controllers on the mini-lab to determine the actual performance in comparison to simulation. The outcomes over two trials will be presented along with recommended modifications.

1. Introduction

One of the main complaints of students in the mechanical engineering classical controls course at UMR (ME279) is that the material covered is too theoretical in nature, and the examples provided in the text are too abstract. ME279 is an introductory control systems design and analysis course that includes classical control system design topics. Topics presented in the course normally include classical feedback control system analysis and design of single-input single output feedback control systems, time domain performance specification and analysis, time domain control system design using root locus techniques, and frequency domain analysis and design. The classical control systems course follows a course in linear systems where students study linear ordinary differential equations for modeling, Laplace transforms applied to mechanical systems, circuits and electromechanical systems. Students in the control systems course are usually required to complete a control systems design project near the end of the semester using MATLAB and Simulink. This is a “paper” project since the students are only required to submit a project report. While the paper project seems to help the students integrate what they have learned, there were still complaints regarding the theoretical, “non-hands-on nature” of the course.

It is generally accepted that learners retain much more knowledge from direct experience than they do from the standard lecture format [1, 2]. However, with the continuing trend of engineering curricular contraction (UMR recently adopted a uniform 128 hour engineering curriculum which reduced the ME curriculum by five semester hours) it is difficult to introduce new laboratories to complement traditional lecture courses. Hence, to address the need for more "hands on" experiences in ME279, we created a "mini-lab" experience for students that required them to apply what they learned during the first nine chapters of Norman Nise's controls text [3] in a laboratory setting. This new project format gave the students a chance to augment the traditional soft design with a small laboratory component by constructing a feedback control system in the laboratory. The written homework was reduced to accommodate the additional work required for the mini-lab.

The incorporation of a mini-laboratory project into the traditional lecture course was tested during two recent semesters in the department of Mechanical and Aerospace Engineering and Engineering Mechanics at the University of Missouri-Rolla. The mini-lab project required students to build a motor speed control. The second mini-lab required the students to build a DC motor angular position control system. Both implementations of the mini-lab experience involved the construction of closed loop control systems using operational amplifiers and electronic components. The systems to be controlled were two small bench-top apparatus designed and built by ME department staff members and faculty. The position control experimental setup used is shown in Figure 1. A voltage control input drove a servo amplifier that controled a DC motor, flywheel, and feedback sensor. Students were asked to design a closed loop feedback control system that met specified performance requirements.

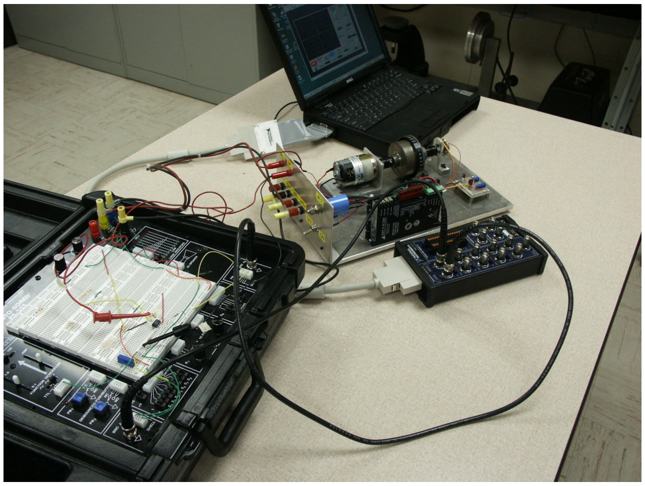

Figure 1. Position control experiment.

The integrated mini-laboratory experience was part of an on-going effort within the department of Mechanical Engineering to augment traditional lecture style courses with practical design experiences featuring hands-on work for students consistent with the current educational opinion in engineering education [2, 4, 5, 6]. This effort provided an opportunity for students to see direct applications of their course theory very close to the time that it was presented in course. The laboratory experience was inherently multidisciplinary in nature and included analysis, design, simulation, prototyping and troubleshooting components. This paper will describe the equipment developed to conduct the mini-laboratory projects, sample mini-lab procedures, and tools being used to assess the impact of the use of mini-lab projects among students.

2. System Apparatus

The contents of this section describe the physical electromechanical system for which students to develop analog control systems. Velocity and position control were studied in successive semesters. In both cases all students were required to participate in the laboratory experience. The two configurations have some common components that we discuss first. Space limitations prohibit complete explanation of the implementation details, but these will be presented thoroughly in a subsequent full-length journal paper.

2.1 Common Components

Schematic and functional block diagrams of the system are shown in Figures 2 and 3 respectively. Components of the system are: (1) an Advanced Motion Controls 12A8K servo amplifier, (2) a permanent magnet DC drive motor labeled M1 and a sensing element to provide the feedback signal. For the velocity control case we used a second DC motor configured as a tachometer generator. For the position feedback configuration we used a series connection of three potentiometers connected between ±12 V control signal power supply. The front panel of the apparatus has binding posts for a 24 V drive motor power supply, ±12 V control system power supply, common ground, drive motor input and feedback voltage output. The front panel also has a potentiometer that can be used to reduce the input voltage seen by the servo amplifier. This allows us to change the transfer function open loop gain so that different lab groups may have a slightly different design problem to work. We use a toggle switch on the front panel to disable the control system if necessary during testing.

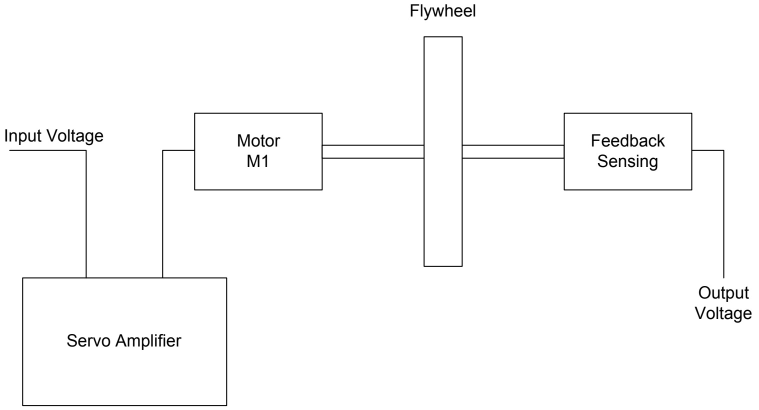

Figure 2. Electromechanical open loop system schematic.

The 12A8K servo amplifier is a DC motor servo amplifier with control mode features including direct tachometer voltage and position feedback voltage inputs. We did not use these features in the experiments describe here but rather configured the 12A8K in an open loop mode so that students could provide their own feedback control circuits. We may exploit these features in other types of experiments and classroom demonstrations in the future. The 12A8K produces a pulse width modulated (PWM) motor drive signal that is proportional to amplifier input voltage. Input voltage controls the duty cycle of the PWM signal, and consequently, average current supplied to the drive motor and average torque produced by the motor.

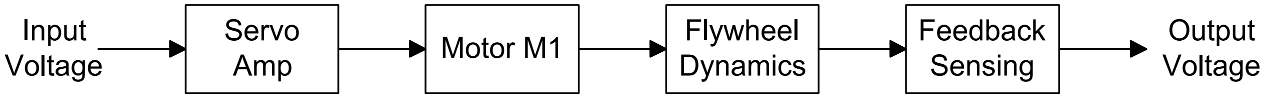

Figure 3. Electromechanical open loop system block diagram

The motor rotor and flywheel moments of inertia are dominating parameters in the dynamic equations for the system. There is also a small amount of damping due to bearing friction and the feedback sensing components. The system dynamics are not linear. However, linear approximations at known operating conditions are sufficient for feedback control design purposes. In the following discussion we describe aspects of the apparatus that are specific to the velocity and position control configurations.

2.2 Angular Velocity Control

A schematic for the velocity control is shown in Figure 4. The reference voltage supplied to the servo amplifier is used to adjust the duty cycle of constant amplitude output pulses produced by the servo amplifier. A higher reference input voltage for the servo amplifier causes the “on time” for output pulses to be longer. Lower reference input voltage causes low “on time” for the output pulses. By changing the duty cycle (ratio of on-time to off-time) of the motor drive voltage we change the average current supplied to the motor being controlled. Higher motor current causes higher motor torque and in steady state this drive torque matches opposing torque due to system damping which is proportional to speed. So as the input voltage supplied to the servo amplifier is there is an increase in the steady state speed of the flywheel. Step changes in servo amplifier input voltage cause a speed transient response that is approximately first order and linear.

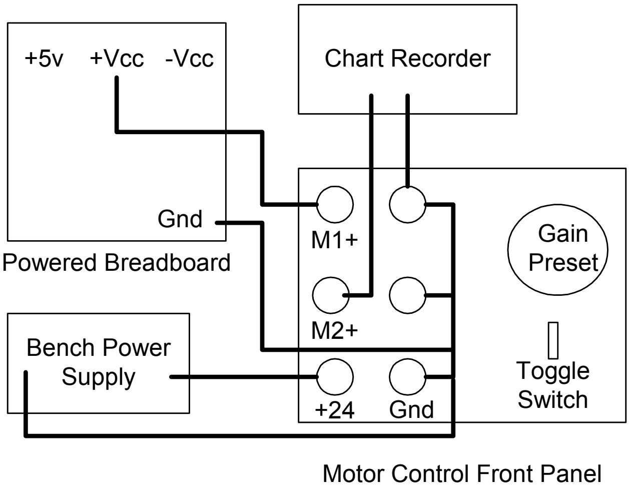

Figure 4: Speed control open loop system wiring diagram

For the speed control configuration we use a second permanent magnet DC motor, labeled M2, that is directly coupled to and driven by the flywheel. In this case torque transmitted through the flywheel is used to generate an output voltage at the terminals of M2 that is proportional to flywheel speed. Tests performed in the laboratory show that the system described above can be closely approximated by a first order transfer function. To determine the transfer function we started with the system at rest and applied a 12.0 volt input signal to the servo amplifier. As the flywheel angular velocity increased we measured M2 DC output voltage using a digital multimeter. The generator output voltage reaches a steady state value of 8.0 volts as the flywheel reaches full speed. Settling time for the system is approximately 25 seconds. The data given here is sufficient for students to determine a first order transfer function for the open loop system.

2.3 Angular Position Control

For the position control laboratory exercise the input side of the open loop system is essentially the same as above. A non-zero input voltage, either positive or negative, produces driving torque at the flywheel shaft, in either the clockwise or counter clockwise direction, which causes motion in the respective directions. To detect angular position of the flywheel we coupled it directly to a 100 KΩ, off-the-shelf, rotary potentiometer. Trimming potentiometers on either side of the feedback potentiometer provide a way to fine tune sensitivity and offset. Physical limitation of the potentiometer used limits the range of motion for the flywheel to ±120 degrees.

Due to the nature of the position control apparatus it is not possible to directly determine, experimentally, the open loop transfer function of the system. We chose to identify the open loop transfer function indirectly in this case and give this to students in order for them to complete their designs. To set this up, we created a proportional control system with (approximately) unity feedback gain and unity controller gain. We then adjusted the servo amplifier and apparatus front panel potentiometer to yield an under-damped, closed loop system with overshoot set at approximately 100 % and settling time approximately 0.75 seconds. A laptop based data acquisition system was used to capture step response data that we then used off-line to identify an approximate open loop transfer function for the apparatus.

3. Mini-Laboratory Experience

In both cases the basic structure of the mini-laboratory experience was similar. Students were provided with background information describing the nature of the electromechanical system to be controlled and provided with reference material. The students then completed control system designs using analytical techniques learned during course lectures and homework exercises through out the semester. Control system designs were supported using simulation studies conducted with Matlab and Simulink. The pre-laboratory work constituted the initial phase of the laboratory experience, prepared students for actually developing physical control systems, and were completed individually by each student in the course. During the second phase of the experience, students divided into laboratory groups ranging from 2-4 students per group and conducted the in-lab portion. The experiences differed, somewhat, between the two apparatuses, and these differences are described in brief below.

In the final phase of the mini-lab experience, students were asked to summarize the results of the laboratory in a final written report given to the course instructor. The speed control configuration was presented in the first offering of the mini-lab. We used the experience gained and student feedback to modify the presentation of the position control mini-lab.

Students had access to or were provided with the necessary tools to complete the control system project designs and prototypes. Instructors provided written problem statements to the students describing the apparatus, giving the necessary open loop system data, and a set of design objectives based on desired time response characteristics of the closed loop system. General operational amplifier circuit design information was provided in the form of a reference document prepared by department faculty. Additional information for simple operational amplifier circuits is available was the course text. A basic bread-boarding reference document was prepared by laboratory support staff within the department and supplied to students. Root locus based time-response design methods and modeling techniques were covered as a normal part of the course and its prerequisite. Students had access to Matlab and Simulink software packages as well as other software for report preparation and data analysis available in the department's computer learning centers.

4. Impact of the Laboratory Experience

We believe that the "just-in-time" types of small lab experiences similar to those we have described, in conjunction with traditional lecture methods, can have a significant impact in the way that students learn and retain the material. However, there are costs associated with providing these services, and, as part of an ongoing effort, we would also like to measure the impact of the mini-lab experience on student learning and retention.

Our first attempt to measure student learning involved testing the students on control and system theory both before and after their mini-lab experience. An analysis of these results failed to show a significant amount of learning had occurred. To improve upon the precision of our research design we used the so-called wait-listed control method where each of the two classes were given a pre-test at the same time, and a post-mini-lab test following the mini-lab experience of only one of the classes. The other class then conducted the mini-lab, and again, both classes were tested with a similar quiz. We feel that the difficulties we encountered during the first implementation, and the fact that the students were rushed to obtain a fairly large amount of data in a short time contributed to a negative experience for the students. Their negative opinions were reflected in the survey given following the mini-lab project. We believe that the negative student experience confounded any potential gain in learning that might have occurred or could have been measured. In the second mini-lab, the position control experiment shown in Figure 1, we significantly shorted the data acquisition process by using a LabView data acquisition system. We further refined the process by establishing an entire week for the students to build and debug their control designs before installing them and conducting the actual experiment during the following week.

We did not attempt to conduct the wait-listed control group measurement of student learning due to time limitations, but did conduct a similar survey following the project. The students were asked to give their opinion on the survey statements on a scale of 1 (strongly disagree) to 7 (strongly agree). The first two questions regarding student opinion were:

1. I found the motor control project to be fun and enjoyable.
2. The motor control project helped me to better understand control theory.

A different question (question 3) was also posed following mini-lab 2: ME279 should always be taught with some form of laboratory implementation project.

The mean scores and their standard deviations for the three questions are given in Table 1. The mean response to the first two questions indicates mild agreement. The margin of agreement is somewhat wider in question 3.

Table 1. Mean ± standard deviation for questions 1 and 2 over mini-labs 1 and 2, and question 3 from Mini-lab 2.

Question	Mini-Lab 1	Sdev	Mini-Lab 2	Sdev
1	4.065	1.735	4.137	1.561
2	4.761	1.659	4.706	1.695
3	NA		5.176	1.556

4.1 Associated Costs

The speed and position control apparatus described herein were relatively inexpensive and developed using department shop facilities and readily available off-the-shelf components. The bread-boarding equipment, and electronic components used by students were also inexpensive.

Test equipment and facility space were borrowed from other traditional laboratory courses at a time in the semester when these were not otherwise used. So the equipment and maintenance costs associated with mini-lab projects were minimal compared to the potential benefits of the program. There was a higher cost associated with this effort in terms of development and supervision time by the faculty and the department staff. These costs must be offset against potential impact of these program implementations. Thus it is critically important to assess the effectiveness of these types of programs to justify this time and personnel expense.

5. Conclusions and Further Work

We were unable to measure any significant improvement in learning during our first mini-lab, and found only modest enthusiasm for the mini-labs based on question one and two. However, based on their response to question three following the second mini-lab, the students seem to agree that some form of laboratory implementation should always accompany ME279. Student written comments seem to be on the whole rather positive towards having a lab experience – the most common complaint being that they would rather do the lab much earlier than the end of the semester. They were also bothered when the equipment failed to work *exactly* as expected, or when a component broke. We plan to continue to refine our mini-lab procedures, and hope to begin the project earlier in the semester. We are also discussing integrating the ME279 project with the preceding course, ME211 (Linear Systems), to allow the student to develop the system model in ME211, and focus only on the control aspect in ME279. We also hope to attempt the wait-listed control learning measure again. Perhaps with sufficient time, we will be able to accurately asses the impact on student learning made by the mini-lab experience.

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