A Design Exercise for Electives in Control systems

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Abstract

At the University of Nevada, Reno, we strongly believe that effective control system education must include experimental exercises that complement the theory presented in lectures. Preferably, the exercises should include the design and implementation of a control system. Limited resources and a cap on the number of credit hours required for the undergraduate degree make it impossible to offer a laboratory course with every control class in most electrical engineering curricula. We have solved this problem by including a laboratory project in each of our two senior electives. Each project is a comprehensive modeling, analysis, design and implementation of a physical control system. The students are divided into groups and each group must independently complete the design project and submit a formal report summarizing their results and experiences. Each student must submit an individual commentary on the exercise and the experimental results obtained. Student feedback indicates an increased appreciation of the lecture material and an awareness of the limitations of the theory and simulation that was lacking prior to the introduction of laboratory exercises.

I. Introduction

The control curriculum for electrical engineers at the University of Nevada, Reno, 7 required and 3 elective credit hours. At the junior level, students are required to take a three credit hour lecture class and a one hour laboratory. The laboratory was the subject of an earlier paper by the author [1]. At the senior level, the students can take a digital control class, a state-space class or both. Both classes include highly mathematical theoretical derivations which must be justified to our students. The number of credit hours allocated to control is already high relative to other areas and there is no justification for increasing it. In addition, the cost of an additional teaching assistant for each class is beyond the resources of the department.

However, the Angst Control Laboratory where our required laboratory course is taught is already equipped with basic instrumentation and control experiments. Our solution is to include a laboratory exercise that involves modeling, analysis, design and implementation of a physical control system in each of the senior level classes.

Our report on laboratory exercises for senior control electives is organized as follows. First, we discuss the topics covered in our senior elective EE 471 Control Systems II, then the topics covered in the second senior elective EE 476 Digital control. Then we describe the laboratory exercise required in each of the control classes and the relationship between the exercise and the theory presented in lecture. We discuss the formal report that each group is required to submit. We conclude with a summary of our experiences with the laboratory exercises and the feedback we have received from our students and graduates.

II. The Senior Electives

The electrical engineering curriculum at UNR includes two three credit hour senior electives. The first senior elective is mostly a course on state-space system descriptions with an introduction to state-space design using the text by P. Belanger [2]. It also includes a discussion of control system configurations, robustness and sensor/actuator limitations. The second course covers digital control system analysis, modeling and z-domain design. It also includes an introduction to state-space methods for discrete-time systems. It is taught using the author's own lecture notes [3]. Both senior electives avoid some of the more advanced theory that is typically covered in graduate level classes that cover the same topics. Nevertheless, the courses include highly mathematical developments which many seniors find challenging. Both courses include elements of computer-aided control system design. However, some of the limitations of the theory and design recipes are not easily appreciated from the simple problems that can be addressed in lectures and exams.

III. The Laboratory Exercises

In each of the senior electives, we include a laboratory exercise related to the course material. The exercise is
treated as a take-home exam and is worth about 20% of the overall grade. The exercise includes modeling, analysis and design of a control system. Practicing engineers often obtain mathematical models of physical systems by evaluating the system parameters in the laboratory, design a controller based on the mathematical model, then use a more complex model in extensive simulations. The simulations provide an economical means of testing the system before hardware implementation. Hardware implementation is attempted only after the designer is satisfied with the simulation results. Finally, some modification of the design may be necessary to obtain acceptable performance. Trial and error may be necessary at each stage before the desired results are obtained. Our goal was to develop a take-home exam including laboratory exercises that mimic this general sequence of events. An elaborate design exercise is feasible because students are willing to devote more time to a take-home exam than to weekly homework. Design problems suitable for in-class exam must involve little or no trial and error due to time limitations.

Although this may vary from one year to another, we have often used the tank experiment of TecQuipment\(^2\), shown in Figure 1, for our take-home exam. The experiment includes a pump and a system to recirculate water through two tanks. A single tank experiment is obtained by keeping the output valve of the second tank fully open. Alternatively, we use the TecQuipment ball-and-beam experiment, shown in Figure 2, to develop a similar design exercise. The beam angular position is manipulated so that the ball move to the desired final position with its motion satisfying time domain constraints.

Although TecQuipment manuals include interesting experiments, we have chosen to design our own lab exercises so as to tailor them to meet the needs of our classes. Nevertheless, our exercises rely on the information provided in the TecQuipment manuals and include portions of their relevant experiments. For example, the TecQuipment manuals include experimental procedures for modeling their apparatus. Modeling is an important step in our laboratory exercises and the students are expected to use the TecQuipment experiments to obtain their mathematical models.

In each exercise, the students must first evaluate the parameters of the system mathematical model experimentally. For the fluid system, the capacitance of each tank and the resistance of its outlet valve must be calculated. The characteristic curves of the pump and level sensor must also be obtained. The changes in water level in the tank are relatively small so that a linear resistance model of the outlet valve is acceptable. However, saturation in the pump must be included in the mathematical model for the simulation results to adequately represent the experiment. The sensor is approximately linear but includes a significant offset. Similar actuator and sensor limitations are encountered when using the ball-and-beam experiment.

After obtaining a mathematical model for the systems, the students simulate the uncompensated system response and compare their simulations to the experimental results. We use the MATLAB\(^3\) toolbox Simulink for all computer simulations so that nonlinearities can be easily included in the simulations. The students quickly realize that the simulation results are of no use unless the nonlinearities in the system are included in its model. In particular, the pump model must include a saturation block in series with a linear subsystem.

Using a CAD tool such as MATLAB, the students then design a controller for the tank based on its linear model. They learn that the model used for design can be much simpler than that used for simulation provided that the performance of the closed-loop system is checked using the more complex simulation model. The students are given guidelines for the selection of the design specifications but the design specifications themselves are not provided. An important part of the exercise is that the students have to experiment with the system to be able to choose realistic design specifications. This is the only opportunity that students have to choose specifications, since time limitations prevent this in tests and on most homework assignments. Students often believe that design specifications are “cast in stone”. In practice, the design engineer may have some freedom in choosing the specifications so that the design criteria lie in acceptable ranges. In addition, the acceptable ranges for the design criteria are based on an understanding of the physical system and its normal operating conditions.

To implement the controllers, the students use an analog controller unit that is also a TecQuipment product (see Figure 3). For digital implementation, student used the controller and its interface with a personal computer. TecQuipment provides a software package that allows the programming of the controllers they design. Students often implement their analog controllers digitally because this gives better results than analog implementation. With sufficiently fast sampling, there is no need to redesign analog controllers for digital implementation.

For the state-space course, the students are required to design a controller and a full-order observer using pole placement. By the separation principle \([2]\), the controller and observer can be independently designed even when

\(^2\) TecQuipment International of Bonsall Street, Long Eaton, Nottingham, NG10 2AN, England, are equipment suppliers, consultants and project contractors for education and training.

\(^3\) Matlab is a product of the MATHWORKS of Natick, MA.
observer-state feedback is used provided that the observer dynamics are sufficiently fast when compared to the closed-loop control system. The students then simulate the system with full state feedback and with observer-state feedback and compare the results.

The state-space course also includes sections on robust stability and the limitations of sensors and controllers. Students who have observed the variations in parameter values due to modeling imperfections easily appreciate the importance of robust stability. The limitations of the pump (actuator) are clearly demonstrated when students attempt to speed up the system dynamics beyond its capabilities. Errors in measurements and offset are observed in the model of the fluid level sensor. These limitations are explained in the lectures using theoretical analyses [2, Chapter 4]. Thus, the experiment reinforces the theoretical developments of the lecture.

For Digital Control, the students design digital PI, PD and PID controllers and compare their performance. The design demonstrates the use of PI control to reduce steady-state error, PD to improve the transient response and PID to improve both the steady-state and the transient response. The students perform extensive simulations of the system with each controller to verify the design results.

The students then implement their designs in the laboratory and compare experimental and theoretical results. The limitations of simulations based on theoretical models become obvious to the students. Even for this simple system, the mathematical models provide rough estimates of the system behavior and some trial and error is required to obtain an acceptable design.

### IV. Laboratory Reports

Every practicing engineer knows that an integral part of his work is to document his results in a clear fashion that can be understood by his colleagues, managers or customers. We repeatedly relay this message to our students. However, requiring a formal report for every laboratory exercise and rewarding good report writing is the most effective means of emphasizing the importance of good report writing.

For the laboratory exercises in senior electives, we provide a report format for the student but variations on the provided format are acceptable. The report must include:

(i) **Abstract**: A summary of the objectives and main results or the exercise.
(ii) **Background**: A description of the experiment used in the exercise.
(iii) **Design Specifications**: A statement of the design problem.
(iv) **Simulation and Experimental Results**: A summary of the design results including tables, figures etc.
(v) **Discussion**: A discussion and interpretation of the experimental and simulation results.
(vi) **Conclusion**: A statement of the major results of the experiment and their significance.
(vii) **Appendix (Design Calculations)**: All details that hinder the flow of the report but are required for understanding and verification of the results are given in appendices.

Each group of three students submits a joint report but each student must write his own Discussion and Conclusion. The reports must be typewritten using a standard word processor. Students use drawing tools to obtain all the necessary schematics but neat hand drawings are acceptable. Students are told to provide a caption for each figure and refer to it in the text. The quality of the reports is generally good but sometimes suffers in the rush to meet the exam deadline.

### V. Conclusion

Laboratory exercises are an important part of an electrical engineer's education. This view is constantly reinforced by feedback from our Departmental Advisory Committee that includes representatives from local industry. One of the main difficulties with laboratory exercises is that they require resources that may be beyond reach for most electrical engineering departments [4]. For a more complete discussion of the advantages and disadvantages of laboratory exercises, the reader is referred to [5]. Our experience at the University of Nevada, Reno, shows that an effective laboratory exercise can be designed as part of senior elective classes with limited resources.

Computer simulations allow the student to experiment with mathematical models and develop a feel for their limitations. However, the author believes that simulations can never take the place of hands-on experiments. One student commented in his conclusion: "Although we had problems simulating, I did not realize how enormously different they (simulations) would be from our implementation problems". Our graduates, that are currently practicing engineers, also indicated their deep appreciation for the practical hands-on experience that they gained from our laboratory experiments.

Student feedback indicates that theoretical developments in lectures on control systems were only appreciated after the laboratory exercises. Student evaluations of the state-space course included "applying theory to a real system" as one of the best things about the course. While students could follow most of the steps of the derivations presented in the lectures, they had little appreciation for their significance before observing their effects in the laboratory. Several students indicated in their
project reports that the theory made a lot more sense after
the experimental exercise.

One student comment summarizes the overall
experience for the class:
"Overall the exam was a very excited, pressured, and
frustrating struggle for me as well as for the rest of the
class, a lot of fun. This was not the down side; I feel I
learned a lot about control systems here. Most of all, how
incredibly different simulation is from implementation."

References

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