A DAQ in Every Hand – A Model for Increasing Student Engagement and Learning in Undergraduate Laboratory Courses

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Abstract

Large-enrollment, required undergraduate teaching laboratories present a host of challenges in delivering highly effective, profoundly impacting engineering experiences for each participating student. Traditional group-performed laboratory experiences have the benefit of efficient use of expensive apparatus, laboratory space, and scheduling, but may have modest impact on students who are less assertive, or who are less technically advanced or experienced than others in their assigned group. The Department of Mechanical & Aerospace Engineering at the University of Florida, with 1600 undergraduates enrolled, undertook a major experiment in 2009 to redesign two of its required undergraduate teaching laboratory courses – Mechanical of Materials Laboratory and Control Systems Design Laboratory. A strategy was developed to provide a high-touch set of individually conducted laboratory experiences that would provide profound engineering educational experiences for the students. Student feedback indicates these modified courses have largely achieved their pedagogic goal of providing high-impact learning experiences that reinforce theoretical coursework.

Keywords

Design Experiment, Controls Theory, Undergraduate Laboratories

Introduction

Undergraduate engineering laboratory courses present unique challenges in providing students with hands-on experiments that reinforce engineering fundamentals.[1,2] A common practice is to split students into several groups where group members split time on the apparatus or only work on a subset of the assigned lab. This helps minimize the cost of the experimental apparatus and provides a practical solution to large classes where laboratory space and time are limited.[3-5] The Mechanical Engineering Department at the University of Florida used a similar approach in its required laboratory courses but realized a significant portion of students were not actively engaged in their laboratory time and were not meeting the desired learning outcomes. In an effort to improve the student experience, several core changes were implemented:

- Every student performs their own laboratory experiment with his or her personal laptop and student owned USB Data Acquisition Device (DAQ) with National Instrument's LabVIEW programming environment.

- Experimental apparatus are designed as simple but instructive systems that can be replicated for 15 student stations and easily modified or changed from semester-to-semester.
- Teaching faculty are augmented by a significant number (~1:6 ratio of TA to students) of undergraduate teaching assistants who have recently taken the course and performed well.
- Students report their laboratory experiences using common peer-review journal article templates and formatting, such as the IEEE or ASME format.

These changes were successfully applied to both the Mechanical of Materials Laboratory and Control Systems Design Laboratory, and this paper focuses on the implementation, details, and results of the Control Systems course. The changes and student feedback are broadly similar between both courses.

In-lab Experiments

During each semester, four to five experiments are chosen to develop a strong connection between the relevant controls theory and students' intuition. For each experiment, several lab apparatus are built from easily available components that are maintainable and adjustable to student needs. Each student has access to his or her own station during the assigned lab time. The experiments are based on the following core controls concepts:

- System Identification – Students learn to identify unknown constant parameters in an electrical-mechanical system through experimental methods with emphasis on frequency domain/Bode plot and step response methods.
- Bang-bang and Proportional Control – Students get their first experience implementing simple controllers and quantifying their performance by analyzing error signals and controller effort.
- Proportional-Integral-Derivative (PID) and Lead Control – Students develop common industrial controllers for DC motors gaining a unique experience into low-level controller design.
- Vision in Controls – Students are exposed to vision techniques for sensing the environment and implementing controllers that operate on pixel and color data.

To give students practical experience with system identification, DC motors are coupled with an external mechanism to provide interesting system dynamics when excited with sinusoidal signals. In previous semesters, the motor was attached to a mass with springs, creating the spring-mass-cart system shown in Figure 1. Students use LabVIEW to excite the system with sinusoidal voltage inputs and measure the corresponding displacement of the mass to create experimental bode plots. With this information, students can infer important dynamics information about the system, such as the resonant frequency or the spring stiffness.

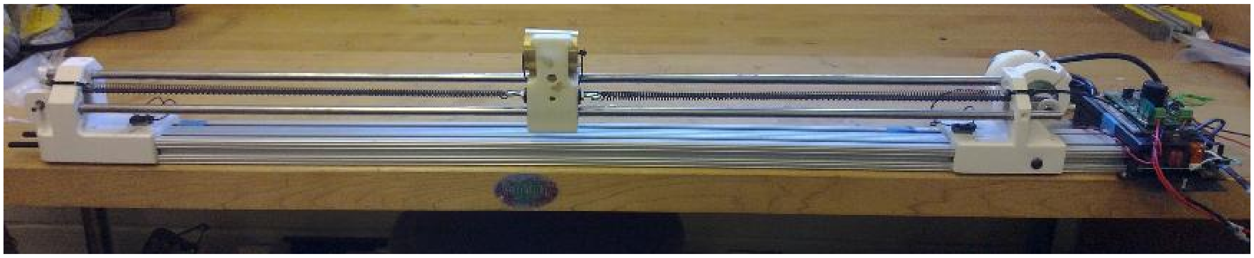

Figure 1: Spring-mass-cart apparatus for exploring system identification principles. Students control the input voltage to the motor and measure the displacement of the mass with a rotary encoder.

The 2nd and 3rd concepts teach students how to fully implement various control strategies instead of using prefabricated solutions. Bang-bang and proportional controllers have been taught using light bulb systems with thermocouples or illumination sensors, where students must regulate the temperature/brightness on the surface of the bulb using feedback from the thermocouple/illumination sensor. This provides students with tangible feedback on the merits of these two controllers. Students also begin to learn the importance of controller gain selection and saturation since a proportional controller with high gains effectively becomes a bang-bang controller. Furthermore, students numerically quantify the performance of each controller by analyzing collected data.

DC motors with flywheels and rotary encoders were selected for students to implement PID and Lead controllers. These types of motors are ubiquitous in controls systems and provide students with excellent feedback. Each station also has a dedicated power supply and H-bridge/PWM motor controller to provide the required voltages. Having students manually move the flywheel by hand with different aspects of the controller engaged reinforces the theoretical concepts of PID control. For example, with only proportional control students experience a spring-like force as they try to rotate the flywheel away from its home position. Derivative control creates a damper effect that students feel as they rotate the flywheel at different speeds. Students also work through different tuning methods to achieve desired performance criteria. Finally, students use their experience from system identification to implement a model-based lead compensator. This gives the students a unique perspective of PID control with tuning techniques in comparison to model-based control.

Figure 2: DC motor and flywheel plant with power supply and H-bridge to help students explore various controller designs.

Finally, students are provided with Playstation Eye Cameras to learn various vision analysis techniques. This camera is inexpensive and can capture QVGA images at approximately 180 frames-per-second, which is sufficient for relatively complex vision application. Students gain experience working with pixel data, thresholding the red-green-blue color scheme, and identifying the position of objects. An example lab implementation is the virtual etch-a-sketch (Fig. 3). Students identified a colored object in the camera workspace and found its centroid location. The centroid served as the drawing point for the etch-a-sketch images, allowing students to draw complex and detailed pictures.

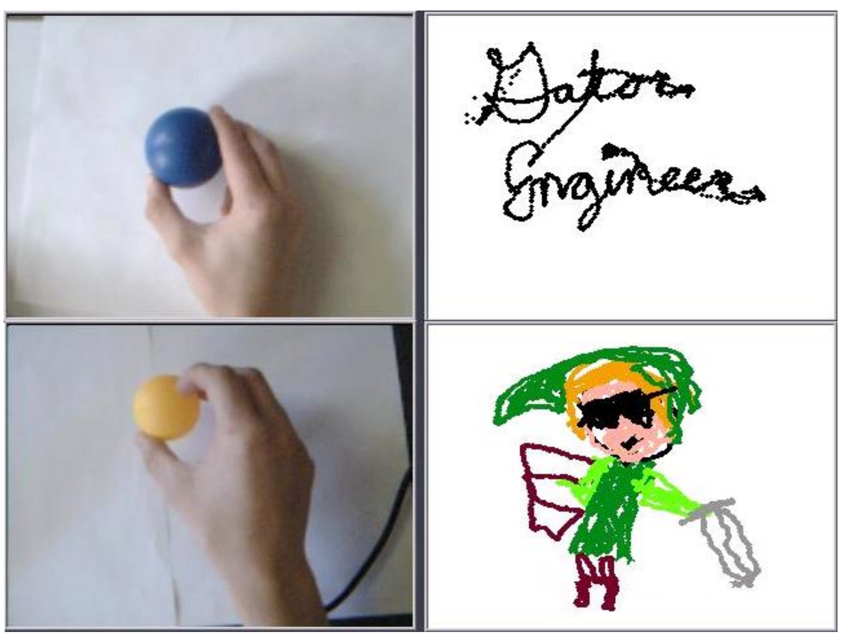

Figure 3: Deanna Gierzak's student submission for the vision-based assignment. A colored object (Left) served as the drawing input to the etch-a-sketch image (Right). Pictured is the Gator Engineering Logo (Top) and a free-hand drawing of a fictional character (Bottom). (Printed with permission from student)

Final Projects

The final projects at the end of each semester combine and build upon the core labs. The goal of these projects is to provide a challenging experience to students that relates to some practical, real-world controls application. The projects are updated or changed each semester, and examples from previous semesters are given in Table 1. While students may find these projects difficult, class evaluations indicate that the projects are rewarding and a great learning experience. The instructor and teaching assistants provide several tips and code snippets to help ensure student success.

All of these projects are multi-input, multi-output systems that require students to combine software written throughout the semester into a single project. Students are allowed to work alone or in groups of two due to the relative increase in work. Multiple copies of each apparatus are built so that enough stations are available for each group during scheduled lab times. Figures 4-6 detail different designs used in previous semesters.

Table I
Controls final project summary for laboratories between 2012 and 2014.

Project	Semester	Core Engineering Concept
Robotic Air Hockey	Fall 2014	Vision, Dynamic Modelling
M&M Sorting Robot	Spring 2014	Vision, State Machine Logic
5 Bar Mechanisms	Fall 2013	Robot geometry, Model-based Design
2-Link Drawing Robots	Spring 2013	Robot Geometry, Feedforward
Inverted Pendulum on Cart	Fall 2012	State-space controls
Lego NXT Segways	Spring 2012	State-space controls

Figure 4: Self-balancing Lego NXT Segway with gyroscope for tilt sensing.

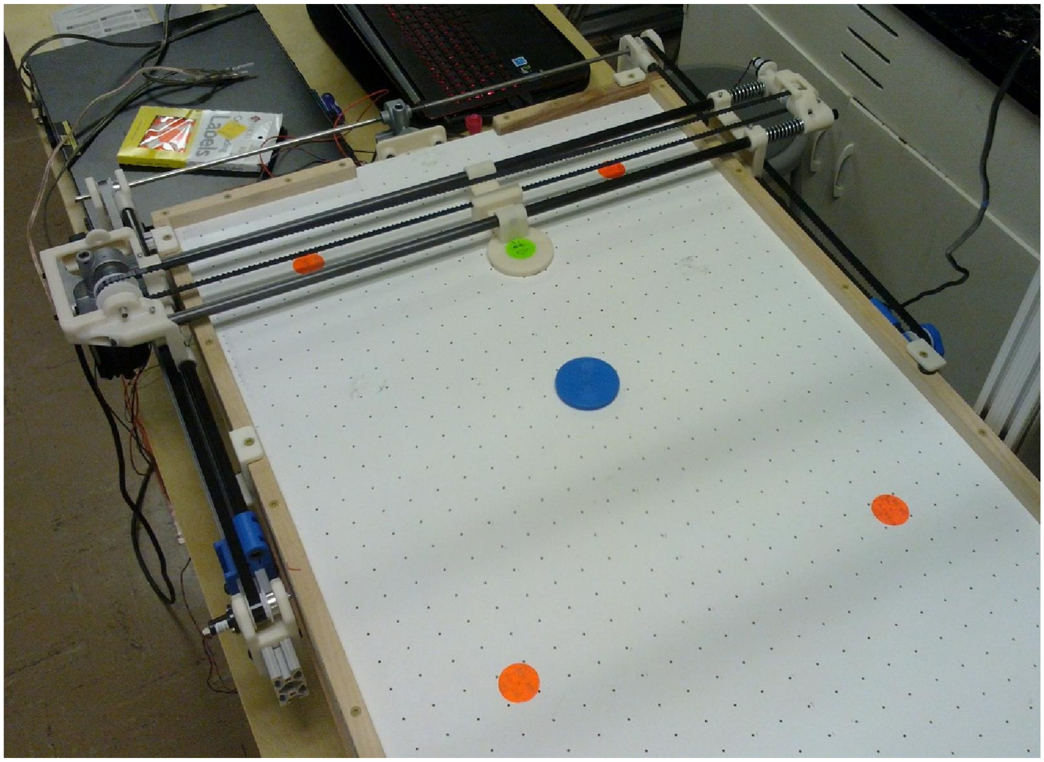

Figure 5: Custom robotic air hockey system final project where students programmatically control a hitting mallet with two DC motors. A camera is mounted above the table to provide feedback of the puck location.

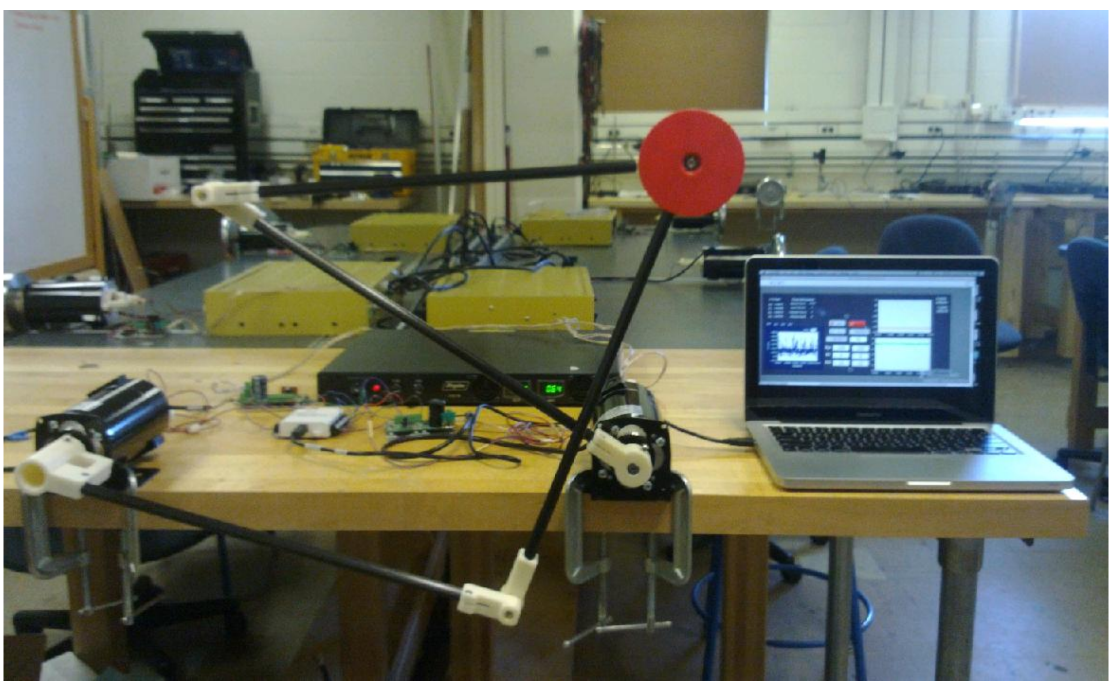

Figure 6: 5-bar mechanism final project which uses two DC motors to position the end effector (red disk) at a desired spatial location.

Student Software

One difficult aspect of implementing these lab assignments is allowing students to focus on learning and mastering the controls material without losing focus of some of the other details, especially programming. These students have been exposed to a programming course before this lab (typically C, MATLAB, or Fortran) but may not be fully comfortable implementing their own algorithms in the LabVIEW programming environment. While programming fundamentals are a necessary and important skill, it is not the main focus of the course. Therefore students are provided with a set of software tools at the beginning of the semester to assist with software design challenges.

Several tools are packaged into a convenient LabVIEW software framework that handles all required low-level programming and provides a structured programming template for students to implement each experiment. The framework is responsible for initializing the DAQ and camera hardware, collecting raw voltage data, sending output signals, saving data, and safely stopping the connected hardware. These details are obscured from the students but are readily available for those who are interested. Without any further work, students have oscilloscope-like features that they can use to explore and control external systems. The framework does not provide any of the logic required for labs, but simply gives students a structured setup to implement their own solutions.

Figure 7: Front Panel view of student framework code in LabVIEW. Students use this code as a foundation to complete all lab experiments, which has built in functionality for analog in/out, digital in/out, file saving, and data graphs.

Course Assessment

To quantify the success of changes to the course, course evaluations from before (2005-2010) and after (2010-present) the course changes were analyzed. Three epochs were chosen over the last ten years to highlight the recent success of the course. The evaluation scale ranges from 1-5, where 1 is poor, 3 is average, and 5 is excellent.[6]

Table II
Student evaluation averages for the Controls Laboratory pre and post course redesign. All averages include multiple semesters and different instructors.

Assessment Question	2005/2006	2008/2009	2013/2014
Communication of ideas and information	2.56	3.73	4.55
Stimulation of interest in the course	2.62	3.80	4.72
Facilitation of learning	2.61	3.77	4.54
Overall assessment of instructor	2.87	3.96	4.76

The following anonymous student comments were chosen to illustrate why students feel the changes have been successful in their own words. While not all students leave the course with the same impression, the goal is to provide a challenging but worthwhile experience that prepares students for practical controls system work.

- I believe this class is a class that really solidifies what is taught in its sister course EML4312. The class is certainly engaging and really helps the students think outside the box in ways that lecture courses cannot.

- This course is fantastic and challenging. You learn a great deal but a great deal of effort is required. The expectations of the students are that they give their best effort and the TAs and instructors do all they can to communicate what needs to be learned/done in order to succeed. OVERALL A GREAT COURSE!!!

- It was a great course. I learned so much more in this class than the actual controls class. Even though it is a difficult subject manner, I now feel more confident in the area and understand all of the basic theories. Because all students have different textbooks, the notes online and additional resources were a great tool.

- I love this class!! Hands down, my favorite course at UF. I had so much fun being in lab, doing the experiments, and analyzing data. I love using MATLAB, and I learned more capabilities in MATLAB by analyzing my data for each lab report. I also enjoyed actually learning how to use LabVIEW.

- This was my favorite class that I've had during my undergrad here at UF. It was a challenging class (especially the final project) but it consistently motivated me to keep trying to understand and learn more about controls.

Conclusions

The Mechanical of Materials Laboratory and Control Systems Design Laboratory have been completely reshaped to better match student expectations and provide individual experiences for students. Students are exposed to custom built apparatus that are tailored to relevant engineering topics. The changes have largely been successful with improved course evaluations and positive responses from students. The courses are continually updated to prevent the labs from becoming stagnant and to match current engineering areas of interest. These changes provide a model that can be adapted to other laboratory classes for providing students with a unique, hands-on lab experience despite large class sizes.

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Ira Hill received his Ph.D. in Mechanical Engineering from the University of Florida in 2013 before serving as a Teaching Fellow for the Control Systems Design Laboratory. He has been closely involved with the undergraduate laboratory courses and the design of new experiments.

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Shannon Ridgeway is the lab director for Mechanical of Materials Laboratory and Control Systems Design Laboratory and has extensive experience in mechanical design, controls, and dynamics from his work with the Center for Intelligent Machines and Robotics (CIMAR). He provides students with a unique perspective and uses his skill set to improve their class experience.

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Dan J. Dickrell received his Ph.D. in 2006 from the Tribology Laboratory at the University of Florida and has been closely involved with engineering education including teaching the Successful Transition and Enhanced Preparation for Undergraduates Program (STEPUP). He currently is a faculty member in the Department of Mechanical Engineering.

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