Manipulation Matters: Isolating the Impact of Lecture vs. Lab Experience in an Undergraduate Engineering Controls Class

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Abstract
Several studies have shown that laboratories that implement interactive learning and cooperative group exercises lead to an improvement in student outcomes as compared to the passive listening characteristic of traditional lectures. The disparity in these experiences is one of many reasons that several undergraduate engineering subjects are taught with both lecture and lab sessions in parallel. At the University of Delaware, Vibrations and Controls is a junior level class in mechanical engineering that has a 3 credit lecture and 1 credit lab that are co-requisites, but are not required to be taken in the same semester. This offers a unique opportunity to analyze student performance for the three distinct groups of students enrolled in lab only, lecture only, and lecture plus lab. We hypothesized that students in the lecture plus lab group would have higher grades in the lecture course than the students enrolled only in the lecture. Our results support this hypothesis.

Introduction
Engineering educators have many concerns regarding the most impactful methods for teaching their students. One of the most prevalent considerations among instructors is whether the pedagogies implemented improve students' engagement with their own learning process.[1] Such learner-centered teaching methods are antithetical to the traditional passive learning lecture. Due to this, progressive instructional methods utilize active learning exercises that have students conduct meaningful activities requiring them to think through their actions. Although active learning encompasses a wide range of teaching methods, a review of studies has shown a trend of increasing students' engagement and improving educational outcomes.[2]

In many university engineering programs, laboratory courses are designated for active learning through hands-on exercises involving object manipulation and practical skill building. For control systems courses, laboratories are often considered an important opportunity to apply the lecture knowledge, bridging theory and application.[3–5] In addition, having students work on tangible, real-world problems can more strongly motivate students to learn information they perceive important.[6]

Engineering laboratories in particular typically task students with team-based exercises requiring collaborative participation, as is the case in this study. The benefits of such active learning lab exercises as compared to passive learning in lecture can include improving knowledge absorption and retention.[7] However, many of these studies are conducted as short in-class activities because these laboratories are most often paired with a lecture taught in parallel, which makes it difficult to distinguish the impact of passive versus active learning methods on student outcomes. However, the Department of Mechanical Engineering at the University of Delaware offers a junior-level Vibrations and Controls class as a 3-credit lecture course and 1-credit lab that are co-requisites but not required to be taken in the same semester. This presents a unique opportunity to evaluate student performance in three distinct groups: lab only, lecture only, and lecture plus lab.

In this study, we assess the performance of the students in these three groups. Based on the positive impacts associated with hands-on experimentation, and considering a previous re-design of the 1-credit lab[8], we hypothesize that the students in the lecture plus lab group will have higher final lecture grades than those in the lecture only group.

Overview of Lecture Course

The course requires students to apply principles of engineering, basic science, and mathematics (particularly differential equations), to analyze and design control systems. The first part of the 3-credit lecture course is devoted to vibration analysis in mechanical systems expressed by linear differential equations with constant coefficients, having a single input and a single output (SISO). We introduce the concepts of damping and resonance, and we determine the behavior of second-order, single-degree-of-freedom systems under certain excitation force patterns. The second part of the course deals with the modification of the dynamical behavior of linear time-invariant systems through feedback control designs. We discuss stability, steady-state and transient performance, and we introduce frequency-based analysis tools such as the root locus and the Bode diagram, and we concentrate on control design using primarily frequency response methods. Most of the control design is done using Bode diagrams, with the main objective being the understanding of how to principally tune the gains of a PID controller based on a transfer function-based description of the plant's dynamics. At the end of the course, students should be able to design a basic PID controller to stabilize an electromechanical system.

The final grade for the lecture course is evaluated as a weighted sum: 10% Class Participation, 20% Homework, 20% Exam 1, 20% Exam 2, and 30% Final Exam.

Overview of Laboratory Course and Experiments

In this 1-credit course that was redesigned last year[9] (and updated since), the students were divided into teams of 3-4 that did not change during the semester. The undergraduate laboratory room has six identical lab tables and three distinct 1 hour 45 minute long lab sections offered throughout the week. We divided the students into two groups that met on alternating weeks, and each group completed four experiments during the semester. Following each of the four experiments, the first characterized as a structured design experience and subsequent were guided design experiences,[10] students prepared reports as a team.

The first experiment in the course served to emphasize the portion of the lecture focused on vibrations. An ECP Model 210 Rectilinear Plant presented a pseudo-ideal mass-spring-damper system with which to verify mathematical concepts presented during lecture. Students were instructed to program the plant with pre-set parameters using the ECP proprietary software. Then, they were to analyze the acquired data using analytical and graphical methods and demonstrate agreement with the mathematical model. The cost for this experiment is approximately $14,950 per station for the Rectilinear Plant and required peripherals.

The second experiment employed an industry standard Siemens S7-1200 Programmable Logic Controller (PLC) in conjunction with a PLC Training Board from Feedback Instruments (Model 34-500, Figure 1) to cover bang-bang control paradigms while providing experience with the industry-pervasive ladder logic programming language. Students were first asked to wire their training board without the controller in the loop to simulate an emergency-off situation in which the controller should by bypassed. Then, students were presented with increasingly complex configurations for the training board and asked to program the controller to have the system behave as described as specified in the lab instructions. These scenarios ranged from implementing discreet on and off buttons to a scenario where a timed run of a motor was triggered by a certain pattern of inputs. Variation in the patterns requires constant interactivity with the system, with each step expanding on previous patterns so there's a clear place to look for an error should one arise. This variation also allowed the experiment to span a wide variety of scenarios analogous to small tasks existing in industry. Since students were expected to have no experience with ladder logic, each task was preceded by a quick tutorial of any new operators they would need. The final task presented to the students was to improve the function of a pre-programmed traffic light algorithm. The starting algorithm merely switched between green and red on a timer. Students were expected to implement yellow lights as well as double-red states, and they were given the opportunity to integrate car presence sensors, a pedestrian crossing, and a mode in which a traffic officer could seize control of the indicator and advance the states manually. The cost of all materials needed for a single station for this lab was approximately $2,200.

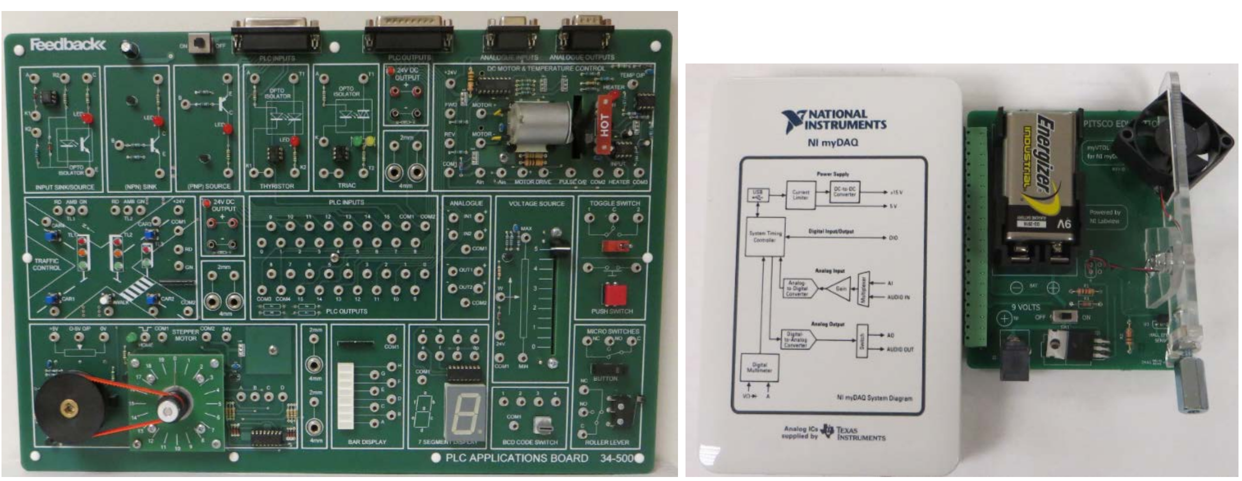

Figure 1: (Left) PLC Trainer Board, (Right) NI myDAQ & Pitsco myVTOL

The third experiment again used bang-bang or on-off control only, but this time to control the temperature of the water in a cheap electric teakettle. Each team was assigned a different type of tea with a different optimal brewing temperature. Then, the students used an Arduino Uno microcontroller, a temperature sensor, and a PowerSwitch Tail (a DC actuated power cord) to create a simple controller that would turn the teakettle off at the appropriate temperature. Additionally, students were required to include an LED in the circuit to indicate when the target temperature was reached. The learning objectives of this lab included exposure to and practice using Arduino hardware and software, a temperature sensor, a digital output device (the PowerSwitch Tail), and a breadboard.

The fourth experiment utilized a National Instruments myDAQ and the Pitsco Education myVTOL (where DAQ stands for Data Acquisition, and VTOL is Vertical Take Off and Landing) – a 1 DOF assembly designed to allow students to experiment with thrust management in a vertical take-off and landing scenario (Figure 1). The purpose of this lab was to allow students to understand the tasks performed by a conventional proportional-integral-derivative (PID) controller, and gain an appreciation for the function of each gain as well as the inner workings of a controller implementation while providing exposure to National Instruments LabVIEW. Three custom LabVIEW Virtual Instruments (VIs) were designed for the exercise, and the students interacted with each to learn about different aspects of the control system. The first VI enabled students to manually control the myVTOL's fan speed and prompted them to keep the fan's height within an acceptable range. The second VI provided a pre-programmed PID algorithm that enabled students to observe the system behaving in an optimal fashion with optimized PID gains. Then, students were directed to vary each of the gains independently, then in tandem, to visualize each gain's effect on the system's behavior. Finally, students were to tune the system's gains themselves to meet settling time and overshoot constraints. The optimized gains were not made visible to students to avoid providing any prior notion as to what any given gain should be. The third and final VI provided a shell in which students built their own PID algorithm within LabVIEW based off a provided block diagram. The shell provided all the I/O functionality, as well as shift registers to handle recursion such that the students would be able to work through the problem without any prior LabVIEW programming experience after a brief tutorial on the LabVIEW environment. It also included ways to probe the contribution of various terms to pinpoint any errors they might have. Students were given liberties over their implementations, and could build in any optimizations or improvements they saw fit until they were satisfied with its function. The hardware cost for this experiment was approximately $350 per station.

Each team of 3-4 students writes a team lab report following each of the four experiments. Each of the lab reports is worth 25% of the final grade, and is evaluated with a rubric that includes point values for each section of content as well as technical writing.

Methods

For the Fall 2016 semester, there were 153 students in the 1-credit lab, 6 of whom were not concurrently enrolled in the lecture. Similarly, 152 students were enrolled in the lecture, 5 of whom were not currently enrolled in the lab. Students were divided into three groups: lab only (6 students), lecture only (5 students), and lecture plus lab (147 students). In this particular semester, the lecture course was divided into two sections, each taught by a separate instructor (Profs. X and Y). The sections shared teaching assistants, discussion sections, exams, assignments, and grading scheme. A different instructor, Prof. Z, taught the lab course. Lab content was coordinated with Profs. X and Y to ensure alignment.

Initially, a one-way ANOVA was used to determine if there were differences in final grades between the three groups. Final lab grades were used for the lab group, final lecture grades were used for the lecture group, and final lecture grades were also used for the lecture plus lab group. A Tukey-Kramer post-hoc test was used to compare different pairs of means to determine which were significantly different from each other. Based on these results, a further comparison was made between the lecture only and lecture plus lab groups again using a one-way ANOVA to compare the means between the final lecture grades. In all cases, the final letter grades were converted to a numerical score according to Table 1 to facilitate statistical comparison, and significance was determined at the $p<0.05$ level.

Table 1: Mapping between final letter grade and numerical score used for statistical comparison

Final Grade	**Numerical Score**
A	11
A-	10
B+	9
B	8
B-	7
C+	6
C	5
C-	4
D+	3
D	2
D-	1
F	0

Results and Discussion

The results of the one-way ANOVA with the Tukey-Kramer post-hoc test (Figure 1) indicate that although there was a significant difference between groups ($p=0.02$), and a significant difference between the lab only and lecture only groups, the difference in the mean final grades between the lab plus lecture and lecture only groups was not significant.

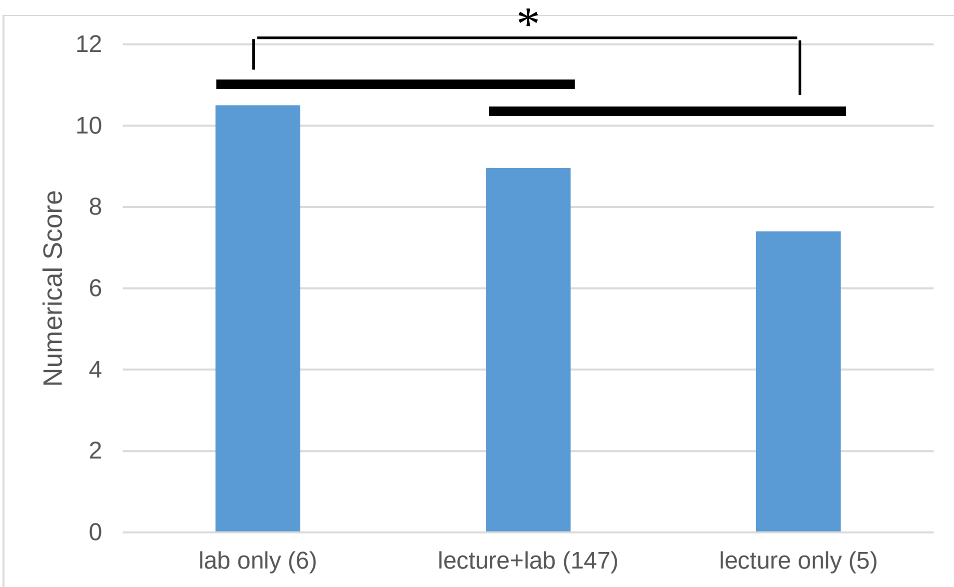

Figure 2: Mean final grades for lab only, lecture plus lab, and lecture only groups. Pairs of means indicated by horizontal lines are not significantly different from each other (Tukey-Kramer method, p>0.05). The asterisk indicates a significant difference in final grades between the lab only and lecture only groups. The number in parenthesis after the labels on the horizontal axis indicate number of students in each group.

A subsequent one-way ANOVA between these later groups indicated that although the mean for the lecture only group is notably lower, the difference was not quite significant (p=0.065, Figure 3). The most likely explanation for the lack of significance is that there were 147 students in the lecture plus lab group and only 5 students in the lecture only group, so a power analysis shows that a greater difference in the means would be needed for the ANOVA to result in statistical significance.

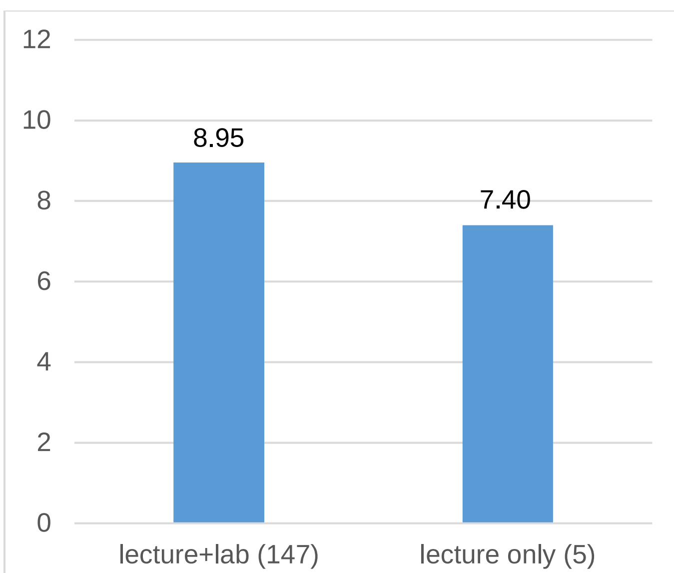

Figure 3: Mean final grades for lecture plus lab and lecture only groups (p=0.65).

Additionally, although a p value of 0.05 is commonly used as the significance threshold, an argument could be made that the threshold could be moved to 0.10 because the relative cost of a false positive is low, and we could not control for the relatively small number of students in the lecture only group. Nevertheless, our data demonstrate that the addition of the lab co-requisite to the students enrolled in the lecture makes a notable, if not significant, difference in their final lecture grades.

Future Work

Although the positive effects of hands-on laboratory instruction have been noted through decades of research, this study is a first step towards demonstrating such an effect in a common mechanical engineering course (Vibrations and Controls) often divided into separate lab and lecture sections. Further research needs to be conducted as to whether the notable difference between final grades in the lecture plus lab and lecture only groups was because of active hands-on learning, or due to other factors. For example, students that chose to take the lab separately from the lecture are sometimes struggling with their workload so choose to delay the lab course, which could be a confounding factor. There were also two different instructors for the two different lecture sections. Although they collaborated and integrated the classes well, differences in teaching effectiveness could alter the results. Additionally, it is not clear if this notable difference is repeatable, so the same analysis will be performed in subsequent years. Finally, it could be insightful to use more than just the final letter grade for comparison. For example, exam or homework scores from the lecture section could be compared with individual lab report grades, especially when these gradable events are temporally aligned, to understand more precisely when and where hands-on laboratory instruction has the most impact.

However, demonstrating that hands-on experimentation yields better outcomes in final lecture grades is not the ultimate goal of this work. Since others have already demonstrated this correlation in other contexts, we recognize this work will only make a small contribution to that already large body of literature. The ultimate goal is to better integrate more effective teaching practices throughout the curriculum. Local evidence of the effectiveness of applying evidence-based teaching methods is necessary to convince other faculty both internal and external to the department that adopting such strategies has quantifiable benefits. This study is a step in that direction that demonstrates that it is clearly possible to replicate the results of effective teaching methods developed elsewhere within the context of our curriculum constraints.

References

1. Turns, J., Eliot, M., Neal, R. & Linse, A. Investigating the teaching concerns of engineering educators. *J. Eng. Educ.* **96,** 295 (2007).
2. Prince, M. Does Active Learning Work? A Review of the Research. *J. Eng. Educ.* **93,** 223–231 (2004).

3. Dorato, P. Undergraduate control education in the US. *IEEE Control Syst. Mag.* **19,** 38–39 (1999).
4. Bernstein, D. S. Enhancing undergraduate control education. *IEEE Control Syst. Mag.* **19,** 40–43 (1999).
5. Antsaklis, P. *et al.* Report on the NSF/CSS Workshop on New Directions in Control Engineering Education. *IEEE Control Syst.* **19,** 53–58 (1999).
6. Albanese, M. A. & Mitchell, S. Problem based Learning: A review of literature on its outcomes and implementation issues. *Acad. Med.* **68,** 52–81 (1993).
7. Menekse, M., Stump, G. S., Krause, S. & Chi, M. T. H. Differentiated Overt Learning Activities for Effective Instruction in Engineering Classrooms. *J. Eng. Educ.* **102,** 346–374 (2013).
8. Roberts, D. & Borowski, A. A revised undergraduate controls lab featuring exposure-based experiences. in *Proc. ASEE Annual Conference & Exposition* (2016).
9. Roberts, D. & Borowski, A. A Revised Undergraduate Controls Lab Featuring Exposure-based Experiences. in *Proc. ASEE Annual Conference & Exposition* (2016).
10. Dhaouadi, R., Al-Assaf, Y. & Rehman, H. Introducing the Guided Design Experience in Control Engineering Education. *Int. J. Eng. Educ.* **28,** 563–571 (2012).