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Evaluating the Effectiveness of an Affordable and Portable Laboratory Kit for an Introductory Control Systems Course

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ABSTRACT

Laboratory kits allow students to take home laboratory equipment to complete experiments on their own time. Because of the lower cost, laboratory kits expand access to hands-on experiences for online courses and to budget-strapped campuses. Although students like laboratory kits, no previous studies compared student learning objectives on assignments using laboratory kits with existing laboratory equipment. We conducted a quasi-experiment to compare students' achievement of learning and their experience in the instructional laboratory for two offerings of an introductory control systems course. Half of the laboratory sections in each offering used the existing equipment, while the other sections used a new kit. The objectives of the laboratory experiments were the same for both types of equipment, and the instructions were as close as possible. In order to assess the students' achievement of the learning objectives and understand the students' experience, we collected a variety of data, including graded laboratory reports, end-of-semester surveys, focus groups, student reflections after each laboratory, midterm exam scores, final exam scores, and control systems concept inventory scores. This comprehensive assessment method may be of independent interest. Based on the data collected, we found no significant differences in the achievement of the learning objectives or in the students' experiences.

Key words: undergraduate, laboratory, learning objectives

INTRODUCTION

Instructional laboratories are a common experience for all undergraduate students majoring in engineering because laboratory experiences help link theory to practice (Feisel and Rosa 2005). Unfortunately, traditional on-campus laboratories require engineering departments to address challenges such as such as budget constraints, space limitations, class size, and limited teaching resources (Borgstrom et al. 2012, Dixon, Dawson, and Costic 2002, Ionescu et al. 2013, Khan, Birchfield, and Singh 2012). Additionally, as engineering departments offer online courses, they need to provide laboratory experiences for off-campus students (Aktan et al. 1996, Boubaker 2012, Hyder, Thames, and Schaefer 2009). Laboratory kits, an alternative to traditional on-campus laboratories, can solve many of the challenges listed above. Kits cost less than traditional laboratories and allow students to take home laboratory equipment to complete experiments on their own time (Sarik and Kymissis 2010, Stark et al. 2013). Because kits are portable, they can also be shipped to students in online courses (Martinez et al. 2016). While a laboratory kit is a viable alternative to traditional laboratories, the students should still able to achieve the intended learning objectives. This study compares student achievement of learning objectives to show that laboratory kits can be an effective alternative to traditional on-campus laboratories.

BACKGROUND

This section highlights laboratory kits of similar cost across engineering disciplines. Then the section discusses specific details about control systems laboratories and kits.

Engineering Laboratory Kits

Laboratory kits have become popular because the cost of the required hardware has decreased (Sarik and Kymissis 2010). The contents of a kit depend on the learning objectives of the laboratory and are assembled by the instructor (Sarik and Kymissis 2010, Borgstrom et al. 2012), adapted from an existing kit (Stark et al. 2013), or purchased as a complete kit such as Lego Mindstorms NXT (Cruz-Martin et al. 2012, Kim 2011, Wadoo and Jain 2012).

The literature includes examples of laboratory kits that are similar in cost. The Arduino prototyping kit designed by Sarik and Kymissis (2010) costs about $95 and is designed for a multidisciplinary course on perception, light, and semiconductors. The Mobile Studio IOBoard described by Millard, Chouikha, and Berry (2007) has multiple versions ranging in price from $80 to $130; it is primarily used in undergraduate circuits courses.

Control Systems Laboratories

Laboratory experiences in control systems are especially important because it is difficult to illustrate, with traditional lecture, the complexity and nuance of applying control system concepts to a physical system (Aktan et al. 1996, Dixon, Dawson, and Costic 2002, Kelly and Moreno 2001). In a control systems laboratory, students typically learn to build a physical system, model and analyze the system, develop a controller to meet performance requirements, simulate the controller and system, observe the physical system, collect the data, and use the data to improve the system model or control tuning (Aktan et al. 1996, Dixon, Dawson, and Costic 2002, Ionescu et al. 2013). Although Leva (2003) believes the controls laboratory experience should prepare students for a career in control systems, these skills can also benefit students who choose not to pursue such careers. Experiments based on DC motors can help students acquire these skills for controls laboratory experiences (Gunasekaran and Potluri 2012, Kelly and Moreno 2001). It is straightforward to control the position of a DC motor with a proportional-integral-derivative (PID) control (Kelly and Moreno 2001). Small DC motors with low input power are easy to integrate into laboratory kits.

Kits have been designed for control systems courses. Students use the Science and Engineering Active Learning (SEAL) System to develop a cart with an inverted pendulum attachment (Borgstrom et al. 2012). The SEAL System kit costs about $100 plus $179 for a myDAQ from National Instruments (Borgstrom et al. 2012, Studica 2014). The MESAbox uses an Arduino and costs approximately $180 (Stark et al. 2013). The MESABox kit includes multiple motors and sensors and is based on an off-the-shelf kit from Sparkfun that contains more components than required for the targeted course. The laboratory experiments designed for the MESABox cover a variety of controls topics including using the Arduino programming language and wiring all of the circuits. Gunasekaran and Potluri (2012) also explain a version of DC motor control equipment. Their DC motor control equipment includes a motor, gearbox, encoder, and $80 of hardware components to build a traditional laboratory apparatus for an approximate total of $400 (Gunasekaran and Potluri 2012, maxon motor 2015).

On end-of-semester satisfaction surveys, students report that they like to use control system laboratory kits (Borgstrom et al. 2012, Sarik and Kymissis 2010). However, these studies do not present data showing whether these kits enabled students to achieve the intended learning objectives.

Two other studies present student ratings of their own proficiency on learning objectives before and after completing the control system laboratory experiments, but there are no direct measures (Gunasekaran and Potluri 2012, Stark et al. 2013). None of these studies directly compares student learning from using a kit with learning from a conventional laboratory apparatus. Therefore, there is no comparison to the previous equipment. This study will compare a new kit with the existing equipment and measure student achievement of learning objectives in a control systems course.

Purpose

In this study, we aimed to measure achievement of learning objectives and the student experience in order to compare two types of laboratory equipment. The baseline group of students used the traditional laboratory equipment, and the treatment group of students used a new laboratory kit. We have demonstrated a method for a thorough assessment of student learning with two types of laboratory equipment. We collected several different types of data in order to determine what effectively measures achievement of laboratory learning objectives, since there was not an existing assessment specifically for laboratories.

We sought to answer the following overarching research question: What were the similarities and differences between the experiences of students who used the portable laboratory kit and students who used the traditional equipment? We refined this question into three more specific questions:

1. Can students using a portable laboratory kit achieve the same learning objectives as students using traditional equipment? The learning objectives are as follows:
   a. Derive the transfer function of a system
   b. Analyze a Bode plot
   c. Design a PID controller
2. Do students' perceptions of their understanding of laboratory concepts differ based on the type of equipment used?
3. Does the student experience (e.g., time spent, satisfaction, feelings towards the laboratory) differ based on the type of equipment used?

METHODS

This section will describe the context of the study, the laboratory kit, and the design of the quasi-experimental study in detail.

Context of the study

Control Systems (GE 320) was selected for study. It is the first of two required control systems courses for all general engineering majors at the University of Illinois at Urbana-Champaign. The GE 320 topics include Laplace transforms, linear mechanical and electrical system modeling, transfer functions, system stability, and feedback control design to specifications. The GE 320 prerequisites are Introductory Dynamics, Intro[duction] to Differential Equations, and either completion or concurrent enrollment in Analog Circuits and Systems. The majority of the students registered for GE 320 are general engineering majors, but students in other majors such as mechanical engineering and industrial engineering can also enroll in the course. Most students take GE 320 during their junior year or fall semester of their senior year. In the fall of 2014, 59 students enrolled in the lecture and one of six laboratory sections. Fifty-three of these students consented to participate in this study. In the spring of 2015, 33 students enrolled in the lecture and one of four laboratory sections. Twenty-one of these students consented to participate in this study. In each semester, half of the laboratory sections used the existing equipment (baseline group) and the other sections used the new kit (treatment group). None of the authors were involved in teaching the course during the study.

During the 16-week semester, each student attended six two-hour laboratory sessions, each with a different experiment to complete. The first two experiments introduced the equipment, the next two experiments developed models of the DC motor, and the fifth experiment implemented three different position control algorithms (Reck 2015, Reck and Sreenivas 2015, 2016). In the last experiment, all students developed a model and controller for a new system. The learning objectives of the laboratory experiments were the same as previous semesters. By the end of the GE 320 laboratory, students should be able to

- Understand the sensors used to measure position and angular velocity of a DC Motor shaft;
- Derive a transfer function of a DC motor using first principles, frequency response, and step response;
- Analyze a Bode plot created from experimental data;
- Design a PID controller for the position of a DC motor; and
- Verify a controller meets specifications with the real DC motor.

The experiment instructions were kept as close as possible between the two types of equipment (Reck 2015, Reck and Sreenivas 2015, 2016). The laboratory experiments for each type of equipment were the same for both semesters. Students worked in groups of two (or three if necessary) to complete the experiments. However, they submitted individual answers to pre-lab and post-lab exercises and individual two-page laboratory reports.

Description of the new laboratory kit and existing equipment

We developed a laboratory kit for GE 320 that would cost less and require less space than traditional laboratory equipment. We selected the components of the kit so the students could achieve the learning objectives of the existing laboratory experiments. Before each laboratory experiment, the research team and the laboratory teaching assistants (TAs) tested the kits to ensure that the students could complete the experiment with the kit. Our kit had a target budget of $100 because this approximated the cost of other affordable kits and engineering textbooks (Millard, Chouikha, and Berry 2007, Sarik and Kymissis 2010). To ensure portability, we designed the kit to fit in a shoebox and weigh less than a pound. Even though our kit was portable, the department purchased six kits for students to use in

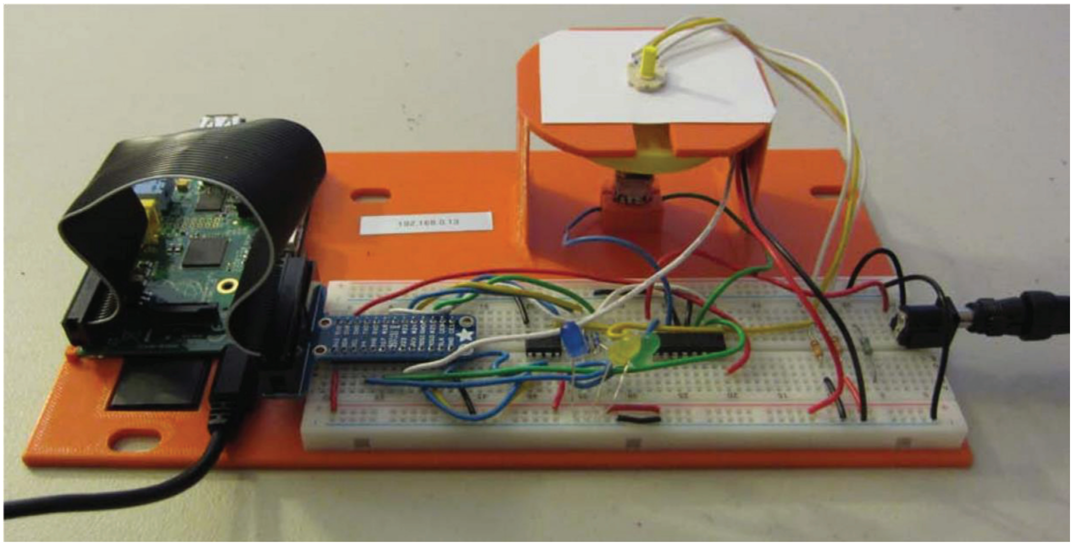


Figure 1. New laboratory kit for GE 320.

the laboratory under the same conditions as the existing traditional equipment used in the course. We opted to use the kits in a traditional laboratory setting to limit the number of variables in the study. The new kit designed for GE 320 consisted of a Raspberry Pi (a single board computer), DC motor, a 3D printed stand, and the associated sensors (Reck and Sreenivas 2016). It cost about $130. A photo of the kit appears in Figure 1. A demonstration video of one experiment using the kit is available https://youtu.be/6YbIXOLdz0I. The existing equipment included an analog computer, DC motor, sensors, oscilloscope, function generator, and multimeter, together costing about $15,000 per station (Reck and Sreenivas 2015). A photo of the existing equipment appears in Figure 2. In the experiments, students implemented the control system using the Raspberry Pi (kit) or the analog computer (existing equipment). The students in the treatment group used MATLAB and Simulink to implement the control system on the Raspberry Pi. The students in the baseline group wired circuits with operational amplifiers, resistors, potentiometers, and capacitors to implement the control system on the analog computer.

Some readers might think that the technical differences in the equipment used by the baseline (analog) and treatment (digital) groups introduced differences in the experience that were not accounted for in this comparison. However, we carefully designed both the existing equipment and the kit to support the learning objectives above. Although on the surface the baseline and treatment controller implementations appear different, in reality, the students in both groups used classical control system analysis and design methods (e.g., continuous time, PID control) in the fifth laboratory experiment. Both groups designed and simulated a PD controller for the position of a

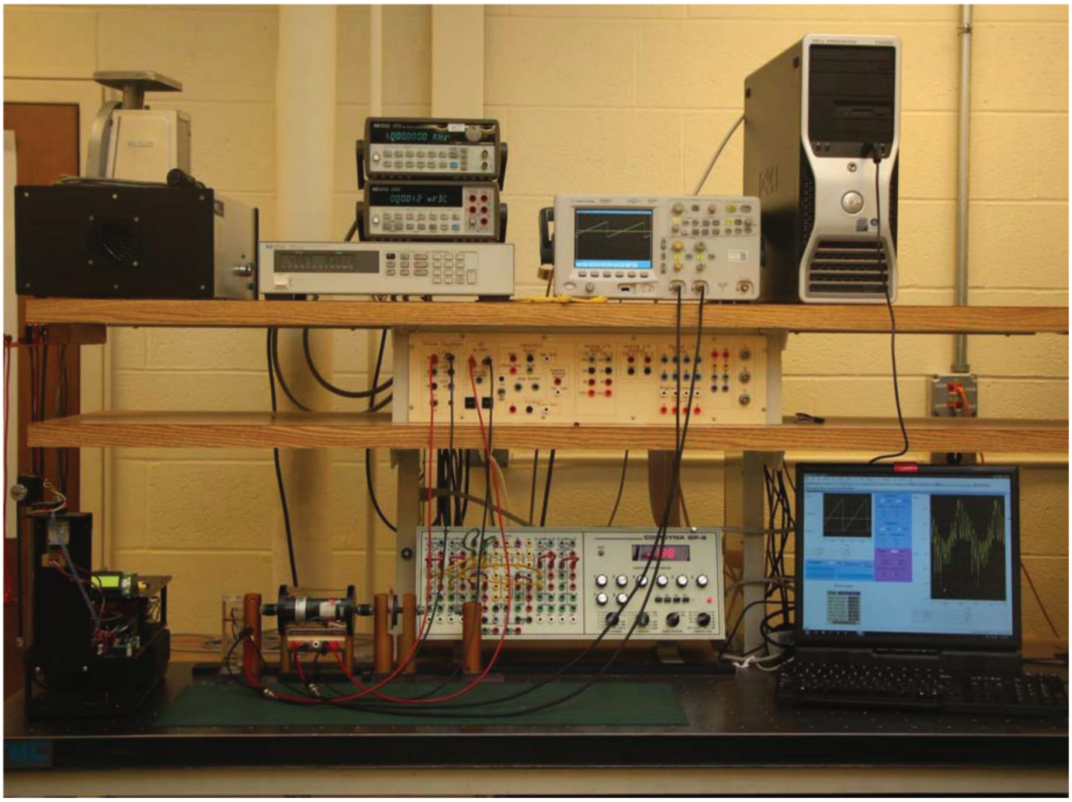


Figure 2. Existing equipment for GE 320.

DC motor in continuous time. Then both groups implemented PD controllers. The students in the baseline group implemented their PD controller design by wiring the analog computer. Simultaneously, students in the treatment group also implemented a PD controller design, this time in Simulink using continuous time and Raspberry Pi interface blocks. Simulink's hardware-in-the-loop interface converted the continuous time system into the digital implementation deployed on the Raspberry Pi at runtime. The following sixth experiment, which built directly on the previous experiment, was identical for both the baseline and the treatment groups and was not changed for this study; the system was non-linear and the controller was executed in discrete time by the interface software. However, the students in both the baseline and treatment groups estimated the linearized system model and designed a PID controller in continuous time.

Procedure

In the 2014-2015 academic year with approval from the Institutional Review Board (IRB #15116), we collected quantitative and qualitative data to compare student learning between the baseline

Table 1. Data collected and corresponding research question.

Question	Labs	FA14: Exams	SP15: Exams	Concept Inventory & Survey	Other
1. Can students using a portable laboratory kit achieve the same learning objectives as students using traditional equipment?					
a. Understand the transfer function of a system	3, 4, 5, 6	1, Final	Midterm, Final	Concept Inventory	
b. Analyze a Bode plot	4	2, Final	Final	Concept Inventory	
c. Design a PID controller	5, 6	Final	Final	Concept Inventory	
2. Do students' perceptions of their understanding of laboratory concepts differ based on the type of equipment used?				Survey items	Reflections, focus groups
3. Does the student experience (e.g., time spent, satisfaction, feelings towards the laboratory)?				Survey items, open response questions	Reflections, focus groups

group and treatment group. The data we collected to answer each research question are summarized in Table 1. At the beginning of each semester, we asked each student to provide consent to participate in the study or to opt out. Students were also allowed to switch laboratory sections. Only one student switched sections in order to use the new laboratory kit.

The quantitative data included exam scores and laboratory report scores. These data were provided by teaching assistants or the faculty member teaching the lecture. In addition, student volunteers completed a concept inventory test and survey on the last day of lecture. The concept inventory test was a multiple-choice test constructed by drawing questions from a test that was previously developed by Bristow et al. (2012) to assess students' knowledge about control systems in mechanical and mechatronics disciplines. Consequently, the original test included questions only about mechanical systems. Since students in GE 320 study both mechanical and electrical systems during lecture, we replaced the last mechanical system question with an equivalent electrical circuit question to ensure a balance between mechanical and electrical systems. A faculty member who had taught GE 320 reviewed the test to ensure the questions were suitable. The student volunteers also rated Likert scale items on an end-of-semester satisfaction survey, which appears in the Appendix. Since few students took the concept inventory and survey in the spring semester, we combined the data for these instruments for both semesters.

All students completed the same experiment in the sixth laboratory session. In this experiment, they repeated some of the same procedures as previous labs on the existing equipment or new kit. Since the sixth experiment was the same for both semesters, these scores were combined as well.

The qualitative data included laboratory observations, reflections from students' individual laboratory reports, open-ended questions on the satisfaction survey, and focus groups. We collected data from the entire class and removed data from students who had not consented to participate in the study.

We used the observations of the fall semester laboratory sessions to supplement the data from other sources as needed. In the laboratory report template, we provided the following prompt to the students for their reflection:

> Please include a reflection of at least 100 words about the experiment. This can include answers to the following questions: What aspects of this laboratory assignment met or did not meet your expectations? How did this assignment surprise, excite, or frustrate you? What lessons did you learn from this assignment? What questions do you still have?

We held two focus group sessions at the end of the spring semester. We solicited student volunteers from both semesters. As an incentive to participate, we provided pizza during the session and gave each student $10 upon completion of the session. All of the student volunteers participated in a focus group. Each session took approximately 30 minutes. Both sessions were audio recorded and then transcribed. The first session included one student from each semester of the treatment group. The second session included one student from the fall semester and two students from the spring semester of the baseline group. The questions we asked during both sessions are included in the Appendix of this paper.

RESULTS

We analyzed the data to answer each research question based on the organization summarized in Table 1. We started with the quantitative analysis of the exam scores and laboratory report 6 grades to measure the achievement of the learning objectives for the laboratory. Next, we performed an exploratory factor analysis and comparison of the survey responses between the two groups. The quantitative survey data measured the students' satisfaction with the laboratory experience and understanding of laboratory concepts. Finally, we coded the qualitative data to identify differences in the students' perceived learning and experience in the laboratory.

The baseline and treatment groups had similar demographics and were representative of the overall general engineering program. Table 2 presents the demographic characteristics of the students in both semesters, based on the course roster each semester. Table 3 includes the sample size of each case for each type of data collected.

Table 2. GE 320 demographics.

		Fall 2014		Spring 2015	
		Treatment	Baseline	Treatment	Baseline
Gender	Male	17	18	7	8
	Female	10	8	3	3
Class Standing	Junior	14	12	4	1
	Senior	12	11	5	8
	Other	1	3	1	2

Exam and concept inventory data analysis

First, we checked whether the students in the baseline and treatment groups performed differently on the exams and on the concept inventory. We started the quantitative analysis of exam data by calculating descriptive statistics and plotting the data in histograms. The exam and concept inventory scores are on a scale of 0 to 100. The exams differed between each semester, because of a change in the instructor. There were two in-class midterms exams in the fall semester and one in-class final exam. There were one in-class midterm exam and a take-home final exam in the spring semester. The descriptive statistics are presented in Table 4. The histograms for each exam and the Concept Inventory are shown in Figure 3. Based on the Grubb’s test for outliers, we identified and removed two low scoring outliers (Barbato et al. 2011). Using the Jarque-Bera test for normality, we determined the data from each group and exam were approximately normal (Thadewald and Bning 2007).

We selected Welch’s t-test to compare the means of each group, because the data were approximately normal and are independent, but the sample sizes and variances were different (Welch

Table 3. Sample size for each case and each type of data collected.

	Fall 2014		Spring 2015	
Data Collected	**Treatment**	**Baseline**	**Treatment**	**Baseline**
Laboratory Reports 1–6	27	26	10	11
FA14 Exam 1	25	25	N/A	N/A
FA14 Exam 2	27	26	N/A	N/A
SP15 Midterm Exam	N/A	N/A	10	11
Final Exam	27	24	9	11
Concept Inventory	17	18	2	1
Survey	21	22	3	1
Focus Group	1	1	1	2

Table 4. GE 320 exam and concept inventory statistics.

	Treatment			Baseline					
	n	M	SD	n	M	SD	Power	Cohen's d	p-value
FA14 Exam 1	25	79.3	13.9	25	82.2	11.7	0.13	0.23	0.42
FA14 Exam 2	27	83.2	9.3	26	84.0	7.8	0.06	0.09	0.74
FA14 Final Exam	27	86.1	7.0	24	83.1	7.8	0.30	0.41	0.15
SP15 Midterm	10	61.8	27.8	11	63.8	16.1	0.05	0.09	0.84
SP14 Final Exam	9	80.1	10.3	11	81.8	9.9	0.06	0.17	0.71
Concept Inventory	19	33.6	10.9	19	34.5	12.4	0.06	0.08	0.82

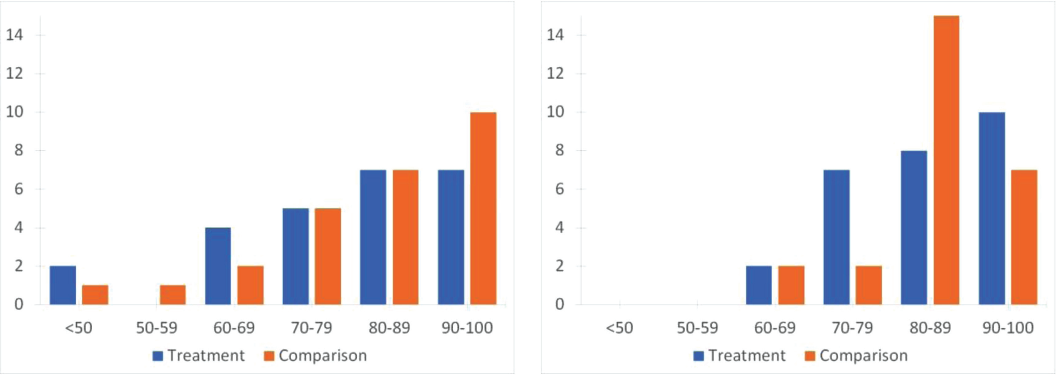
1938). The null hypothesis for each t-test was the mean exam score treatment group and mean exam score baseline group were the same. Based on these t-tests and a significance level of $\alpha = 0.05$, we cannot reject the null hypothesis. The Cohen's *d* (effect size), and power were also calculated with each test; see Table 4.

The power values and effect sizes reported in Table 4 were based on the actual differences in the mean scores. Therefore, the power reported is the probability of detecting a normalized difference in the means that is the reported effect size. For educational tests, an $\alpha = 0.05$ and power of 0.8 ($\beta = 0.2$) are typical values (Creswell 2005). With these levels and the sample size of the fall exams ($n = 25$), there would be an 80 percent chance of detecting a normalized difference (effect size) of 0.8 or larger between the means. In this study, a large effect size would be approximately equivalent to a letter grade. Based on the power analysis and the results presented in Table 4, it is unlikely that there was a large normalized difference ($d \geq 0.8$) in the mean exam scores between the treatment and baseline groups.

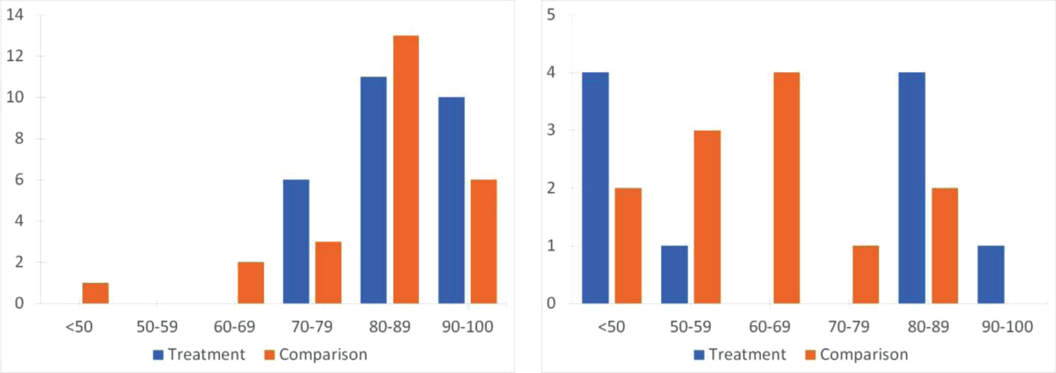
Because we performed multiple t-tests, we considered a Bonferroni-Holm correction (Shaffer 1995). Since most the p-values are significantly above the $\alpha = 0.05$ significance level, Type II error is more of a concern than familywise error. Therefore, we did not apply a multiple comparison correction. The lack of significant differences between the exam and concept inventory scores indicates that the students achieved the intended learning objectives at the same level of proficiency no matter what type of equipment they used in the laboratory.

Validity of concept inventory

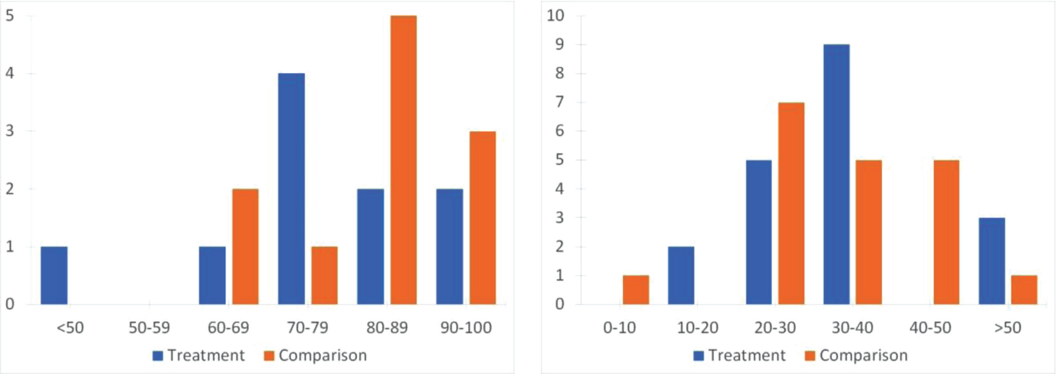
We investigated the validity of the concept inventory test. First, a faculty member reviewed the concept inventory test. He had taught the course in the past, but not during this study. Because of the small sample size, measures of reliability were limited. The Cronbach's alpha for the whole test was 0.13, which is very low. The Cronbach's alphas when excluding each test item were between



(a) Fall 2014 exam 1. (b) Fall 2014 exam 2.



(c) Fall 2014 final exam. (d) Spring 2015 midterm.



(e) Spring 2014 final exam. (f) Concept inventory

Figure 3. Histograms of exam scores and concept inventory test.

0.03 and 0.19, which are below the typical recommended threshold of 0.7 (Peterson 1994, Reck 2016). The concept inventory items were divided into five related subsets. The second and fourth subsets were directly related to the learning objectives of the laboratory, so we investigated each subset as a separate test. This subset analysis did not produce useful results: most of the Cronbach's alphas were negative.

Finally, we calculated the Pearson correlation between each pair of test items. The maximum correlation between two items was 0.46 between item 10 and item 13 and the average correlation was 0.01. Almost half, 75, of the inter-item correlations were negative, but, on assessment instruments, inter-item correlations should be positive. These negative correlations could also explain the low and sometimes negative values of Cronbach's alpha.

Laboratory report 6 grade analysis

Next, we checked whether the students in the baseline and treatment groups differed in their performance in Laboratory 6, which was the same for both groups. In this laboratory experiment, the students applied skills learned earlier in the semester to identify a new system (learning objective a) and to design a controller for it (learning objective c). Since this laboratory experiment was a cumulative experience for the students, we compared the scores on the laboratory reports between each group.

First, we calculated descriptive statistics and tested normality for the treatment and baseline groups; see Table 5. The distribution of the Laboratory 6 scores is in Figure 4. Since the data did not appear to be normal, we used the Wilcoxon Rank Sum test to compare the distributions of the two groups. Based on the Wilcoxon test and an $\alpha = 0.05$, we could not reject the null hypothesis that the distributions are the same. The laboratory 6 report scores show that the students achieved learning objectives a and c at the same level with both types of equipment.

Survey data analysis

We split the Likert-scale items from the survey into two parts: laboratory satisfaction and concepts. The laboratory satisfaction items related to the third research question: does the student experience (e.g., time spent, satisfaction, feelings towards the lab) differ based on the type of equipment used? The items about concepts related to the second research question: do students' perception of their understanding of laboratory concepts differ based on the type of equipment used? Each of the items had four Likert-scale options: strongly disagree (1), disagree (2), agree (3), and strongly agree (4). We performed an exploratory factor analysis (EFA) on each subset of items in RStudio.

Table 5. Laboratory 6 score statistics.

	Treatment			Baseline			Wilcoxon Rank Sum p-value
	n	M	SD	n	M	SD	
Laboratory 6	36	94.2	5.3	35	90.3	8.2	0.1

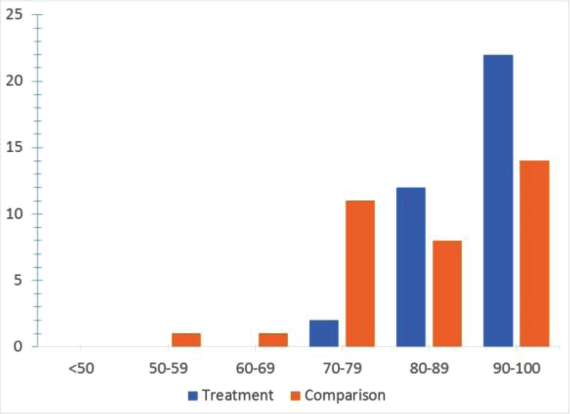


Figure 4. Laboratory 6 report score histogram.

Laboratory satisfaction items

First, we computed the Pearson correlation matrix and checked the Kaiser-Meyer-Olkin (KMO) index, and we determined that EFA was an appropriate analysis for the survey (Tabachnick and Fidell 1989). Next, we estimated the number of factors using the eigenvalues on a scree plot and principal component analysis (PCA). We selected a principal factor solution and an oblique rotation, "oblimin," which is preferred in social science research because oblique rotations can account for correlations between factors (Beavers et al. 2013). After review of the first fit, we decided to remove the following items:

4. The GE 320 laboratory assignments challenged me.
11. I learned skills in the GE 320 laboratory that I could use in industry.
16. The GE 320 laboratory equipment met my expectations.

Then we repeated the EFA with the new set of items. We estimated the number of factors using the same methods and determined the best statistical fit. The items, factor loadings, and Cronbach's alphas are presented in Table 6. The correlation matrix, in Table 7, shows that there is not a strong correlation between any of the factors.

Then we analyzed the responses for each factor in the treatment and baseline groups. Since the factors did not appear to be normal, we ran a Wilcoxon Rank Sum test, on each factor and each of the three items omitted from the factor analysis to compare the distributions of the treatment and baseline groups. The statistics and p-values are summarized in Table 8. After we adjusted the p-values with a Bonferroni-Holm correction, the p-values for all of the factors and removed items were above the significance level of 0.05. Based on these p-values, we concluded that the student experience probably does not differ based on the type of equipment used.

Table 6. Simple factor structure using principal axis EFA with oblimin rotation for satisfaction items (α = 0.86).

	Factor Loadings		
Survey Items	**A1**	**A2**	**A3**
Factor A1: Laboratory objectives and connections with lecture (α = 0.84)			
1. I am satisfied with the GE320 laboratory.	0.87		
3. The GE320 laboratory covered enough content.	0.42		
5. The GE320 laboratory assignments reinforced topics from lecture.	0.58		
7. I achieved the objectives of the GE320 Laboratory.	0.56	−0.31	
9. The GE320 laboratory helped me learn concepts discussed in lecture.	0.72		
12. I did not learn anything in the GE320 laboratory.	−0.54		−0.37
15. The GE320 laboratory met my expectations.	0.53		
6. I understood the objectives of the GE320 laboratory.	0.43		0.56
Factor A2: Laboratory equipment satisfaction (α = 0.64)			
2. I am satisfied with the laboratory equipment for GE320.		0.40	
17. I would recommend that students use the same equipment I used in future GE320 laboratories.		0.99	
Factor A3: Feelings about the laboratory equipment (α = 0.68)			
8. The GE320 Laboratory equipment was easy to use.			0.66
10. The GE320 laboratory equipment was a distraction to learning concepts from lecture.			−0.58
13. The GE320 laboratory equipment aided my learning of course material.	0.38		0.47
14. I felt frustrated with the GE320 laboratory equipment in more than half of the laboratory sessions.			−0.58

Note: the table omits loadings whose magnitudes are less than 0.3

Concept items

We followed the same EFA procedures for the concept items in the survey. The concept items were split into two groups. Items 1-10 included the instructions "The GE 320 laboratory (this includes the pre-lab questions, experiments, and post-lab questions, but does not include homework assignments or lectures) helped me learn the following topics." Items 11-17 included the instructions: "It was easy to understand how to complete the following tasks with the GE 320 laboratory equipment."

Table 7. Factor correlation matrix for satisfaction items.

	Factor A1	Factor A2	Factor A3
Factor A1	1		
Factor A2	0.50	1	
Factor A3	0.15	0.28	1

Table 8. Descriptive statistics of laboratory satisfaction factors and items excluded from factors.

		Treatment (n = 24)		Baseline (n = 21)			
	# of Items	M	SD	M	SD	p-value	p-value adjusted
Factor A1	8	2.22	0.78	2.17	0.85	0.56	1.00
Factor A2	2	2.85	0.74	2.50	0.74	0.03	0.17
Factor A3	4	2.33	0.75	2.60	0.93	0.92	1.00
Item 4	1	3.67	0.48	3.48	0.75	0.46	1.00
Item 11	1	2.25	0.85	2.40	0.86	0.61	1.00
Item 16	1	2.67	0.65	2.76	0.55	0.47	1.00

Note: the students did not omit responses for any of the laboratory satisfaction items.

We started by calculating the KMO and estimating the number of factors. Because the concepts tested by two items, Laplace transforms and MATLAB/Simulink, were not directly related to any other concept asked in these items, they were removed. The summary of factors and respective Cronbach's alphas are in Table 9. The correlation matrix, in Table 10, shows that there is not a strong correlation between any of the factors.

Then we analyzed the responses for each factor in the treatment and baseline groups. We aggregated the responses from each individual item into the corresponding factor. There were 11 total responses missing from the concept items (see column n_m of Table 11). We calculated the descriptive statistics and checked for normality. Since none of the factors or items appeared to be normal, we used a Wilcoxon Rank Sum test to compare the means of the two groups. The statistics and p-values for each factor and the excluded items are summarized in Table 11. Since most of the p-values were near the significance level, $\alpha = 0.05$, we applied a Bonferroni-Holm adjustment to all of the p-values (Shaffer, 1995). After the adjustment, factor B3 was still not above the significance level, so the null hypothesis of equal distributions is rejected. Further Wilcoxon tests indicate that the distribution of the baseline group is shifted to the right of the distribution of the treatment group.

From these results, the students' perceptions of their understanding of system identification (factor B1), implementing PID controllers (factor B2), and system related concepts (factor B4) do not differ based on the type of equipment used. However, students in the baseline group reported that their understanding of control systems and related components (factor B3) was greater than students in the treatment group. However, this difference could arise because only the baseline group actually wired circuits to implement control systems.

Table 9. Simple factor structure using principal axis EFA with oblimin rotation for concept items (α = 0.84).

Survey Questions	Factor Loadings B1	B2	B3	B4
Factor B1: System identification (α = 0.83)				
12. Identify the plant (system) to be controlled using first principles (measuring armature resistance, inductance, etc.)	0.60		0.31	
13. Identify the plant (system) to be controlled using step response.	0.97			
14. Identify the plant (system) to be controlled using frequency response.	0.69			
Factor B2: Implementing PID controllers (α = 0.86)				
15. Design various PID controllers.		0.62		
16. Implement PID controllers with the real motor.		0.90		
17. Test the PID controllers with the real motor.		0.86		
Factor B3: Control systems and related components (α = 0.79)				
1. Circuits			0.79	
4. Types of controls			0.40	
6. Design of control systems			0.50	
8. Design of PID controls		0.44	0.56	
9. Design of lead-lag controls			0.52	
11. Tune sensors used to measure speed and position			0.61	
Factor B4: System related concepts (α = 0.76)				
3. System identification				0.49
5. System stability				0.80
10. Frequency response				0.35

Note: the table omits loadings whose magnitudes are less than 0.3

Qualitative data analysis

We gathered qualitative data to answer the last two research questions: Do students' perceptions of their understanding of laboratory concepts differ based on the type of equipment used? Does the student experience differ based on the type of equipment used? The qualitative data included open-ended survey questions, focus groups, student reflections, and laboratory observations.

Table 10. Factor correlation matrix for concept items.

	Factor B1	Factor B2	Factor B3	Factor B4
Factor B1	1			
Factor B2	0.26	1		
Factor B3	0.36	0.26	1	
Factor B4	0.06	0.19	0.40	1

Table 11. Descriptive statistics of concept factors and items excluded from factors.

	# of items	Treatment (n=24) nm	Treatment (n=24) M	Treatment (n=24) SD	Baseline (n=23) nm	Baseline (n=23) M	Baseline (n=23) SD	p-value	p-value Adjusted
Factor B1	3	0	2.53	0.58	3	2.30	0.78	0.05	0.19
Factor B2	3	3	2.36	0.69	3	2.11	0.81	0.04	0.19
Factor B3	6	1	2.21	0.76	1	2.52	0.79	< 0.01	0.01
Factor B4	3	0	2.56	0.69	0	2.45	0.76	0.24	0.48
2. Laplace Transforms	1	0	2.33	0.70	0	2.43	0.79	0.65	0.65
7. MATLAB/Simulink	1	0	3.21	0.66	0	2.70	0.88	0.04	0.19

We coded the data using hypothesis coding, which applies a predetermined set of codes in order to assess a hypothesis (Saldaña 2013). Following from the quantitative data, we hypothesized that there was not a difference in what the students perceived that they learned or in their experience. Overall, the qualitative data confirms this hypothesis.

We created the predetermined codes based on the research questions and laboratory observations in fall 2014; see Table 12. We used these predetermined codes on the first pass of the

Table 12. Inital codes based by research question.

Research Question	Code
Do students' perceptions of their understanding of laboratory concepts differ based on the type of equipment used?	MATLAB PID Control Bode Plots Scopes Confusion Misconception Learning No learning Remaining questions
Does the student experience differ based on the type of equipment used?	Liked lab Disliked lab Liked equipment Disliked equipment Equipment problem Feeling positive Feeling negative Met expectations Did not meet expectations Helpful instructions Improve instructions TA positive TA negative Too long Frustrations

coding. For the second pass of coding, we split some codes into codes that were more detailed. For example, we split learning into PID, Bode plots, transfer functions, laboratory skills, and connections to professional practice. Finally, we focused the final analysis on data that directly related to the difference in equipment. One of the authors completed all three passes of coding. In between each pass, the research team discussed the codes that were used, the process, and the resulting analysis.

We divided the data into four cases: fall 2014 baseline, fall 2014 treatment, spring 2015 baseline, and spring 2015 treatment. To protect the identity of the students, we gave students in the fall 2014 treatment case pseudonyms beginning with the letter A and students in the spring 2015 treatment case pseudonyms with B. We gave students in the fall 2014 baseline case pseudonyms beginning with C and in the spring 2015 baseline case pseudonyms beginning with D. We gave the teaching assistants pseudonyms beginning with F.

Students' perceptions of their understanding of laboratory concepts

In the reflections, the students mentioned several concepts that they learned including transfer functions, Bode plots, PID controllers, MATLAB, and other laboratory skills. The students were tested on only some of the reported skills, however.

In all four cases, students reported that they learned how to derive transfer functions from experimental data (learning objective a). For example,

> *I think in class it is very easy to write equations but to not really understand where they are coming from, or how they apply to experimental data. I think that the lab is doing a great job of combining the two. (Diane, Experiment 3 Reflection)*

> *It is interesting that sometimes you are able to measure all of the values to find transfer functions. I do not believe that it will always work to find different characteristics of the system. Also there is a lot of error that complies with each characteristic. These can sometimes be compounded because one value must be used to find another value. Overall it was interest [sic] to see that the transfer function could be simplified to a first order system. (Blake, Experiment 3 Reflection)*

Like Diane, other students also reported a better understanding of transfer functions after completing experiments 3 and 4. Blake went further in his reflection in comparing the complexity of measurement, sources of error, and possible simplifications. Blake's reflection illustrates the intended lessons from experiments 3 and 4.

Students in all four cases were able to create Bode plots from experimental data (learning objective b). For example,

> *I found it interesting to see how a Bode plot, which had been a mystery to me, is constructed. … Overall, this lab really helped my conceptual understanding of how a transfer function can cause both a gain in magnitude and a phase shift. (Darren, Experiment 4 Reflection)*

Bode plots are a graphical representation of the frequency response of a system. The students in the treatment groups referred to the frequency response in general, rather than the Bode plot itself.

> *The step response method and frequency method make us [sic] able to obtain the transfer function without mathematical models. It is also more efficient. We do not need to measure to [sic] many parameters, which we did in [sic] previous lab. This advantage can help us obtain the results with less error. (Bert, Experiment 4 Reflection)*

Most students generically commented on frequency response like Bert. Fewer students, such as Darren, mentioned the Bode plot by name. Darren illustrated a better understanding of Bode plots in his reflection. Bert identified advantages of step and frequency response, which is also a useful lesson from experiment 4. Both examples above illustrate achievement of learning objective b.

In all four cases, students learned to implement various PID controllers, identify performance differences between variations of PID controllers, and determine gains for PID controllers. All of these skills are aspects of designing a PID controller (learning objective c). For example,

> *It was very helpful to see how changing the values in the controllers affected the settling time and percent overshoot of the three different types of controllers. The pre-lab was also very helpful in that it showed how controllers are used with transfer functions and how all that information can be used to design controllers to help a system meet design specifications. (Dale, Experiment 5 Reflection)*

> *The aspect of this lab that I enjoyed the most as [sic] creating different control systems for the DC motor. It was interesting to see how the different models affected the output of the DC motor. I also enjoyed gaining a fuller understanding of how a model can be created in Simulink to create a controller. It has been interesting to see how all the labs thus far have come together to create a better understanding of how control systems work. (Bill, Experiment 5 Reflection)*

Dale and Bill identified that there were differences between the three types of controllers implemented and that changing the gains changed the overall performance. However, no student commented on the difference in the gains between the analytical, simulation, and actual solutions. Unfortunately, the latter is also an important objective of experiment 5.

Students' experience

We also used qualitative data to gain insight into the third question: Does the student experience (e.g., time spent, satisfaction, feelings towards the laboratory) differ based on the type of equipment used? In general, we hoped that the overall experience would be similar with both types of equipment. We thought that the treatment sections might complete experiments faster than the baseline sections because we thought creating models in Simulink would be faster and less confusing than wiring the analog computer. However, that did not turn out to be the case. We examined the students' satisfaction with the laboratory, problems with the equipment, the length of time spent on each experiment, the type of instructions, and feelings expressed by the students. In all of these areas, there were only minor differences identified between the treatment and baseline groups.

Multiple students in each case stated that they were satisfied with laboratory experience, and multiple students in each case stated that they were dissatisfied. In every case, there were examples of students who liked the experience and the equipment. For instance,

> *I liked this lab and it connected very well to what we are doing in class. I am liking [sic] how we are slowly building up our knowledge each lab. (Cliff, Experiment 5 Reflection)*

Cliff commented on how he liked that each laboratory experiment built upon skills learned in previous experiments. Throughout the reflections, surveys, and focus groups there were other similar comments, some of them as simple as "I liked this lab" or "This lab met my expectations."

There were also positive comments about both types of equipment in each semester. For example,

> *For me I like how there is a motor and you really can see how the developed in to [sic] motion and the flexibility of the analog computer helped you to switch around the different transfer functions to the one you like. (Dustin, Focus Group)*

> *I also like how the lab was interactive; we had to make changes in real time in order to receive the most accurate results we could. (Albert, Experiment 5 Reflection)*

Dustin and Albert each mentioned a specific aspect of their respective equipment. Other students in all four cases had both specific and general positive comments about the equipment. While there were multiple positive comments about the experience and the equipment, there were also negative comments. The negative comments ranged from specific problems with part of the equipment to more general comments about the experience. For example,

> *The only frustrating part about this lab was making sure to get not only the wiring of the equipment correct, but to also follow the exact steps for the computer programs or else it would crash on you. (Dustin, Experiment 1 Reflection)*

> *I really disliked this lab. I would have much rather had a discussion class. This lab just confused me and did nothing to help me learn the material for exams. (Adrian, Survey)*

Dustin mentioned a very specific problem with the equipment itself. Other students made similarly specific comments about problems that occurred during the laboratory sessions. Adrian expressed a general dislike of the laboratory experience and proposed an alternative; a few other students agreed with him.

In all four cases, students ran into problems during the experiments. While some problems, like signal noise, are expected, some students became frustrated when they encountered some problems. One problem, common to both types of equipment, was obtaining data measurements from scopes. For example,

> *However, I did find it relatively frustrating that our equipment was naturally inaccurate as our voltage values came out askewd [sic] a lot [sic] of the times. The other part I was not thrilled about was that in the [VEE] software, it was extremely difficult to estimate a proper value for our purposes. (Dustin, Experiment 4 Reflection)*

> *The most challenging part of this lab was actually the collect, [sic] analysis and calculation of data. To read the peak voltage and time shift from the scope, it was hard to determine which point to read and thus there were lot of uncertainties. (Brett, Experiment 4 Reflection)*

Both Dustin and Brett commented on the difficulties in obtaining accurate data. Dustin was using Agilent VEE to retrieve data from the Agilent oscilloscopes, while Brett was using the Scope block in Simulink. According to the comments from Dustin, Brett, and other students, reading scopes is a common problem for students.

Similar experiences could have hindered learning for both treatment and baseline students

Beyond problems with the equipment, students specifically identified two other aspects of the experience that hindered their learning. The first one was the length of the experiments, especially experiment 4 and experiment 5. For example,

> *Given more [sic] it would have been interesting to try to systematically vary the gains in each system and plug them in to the transfer functions obtained in the pre-lab to try to see some pattern [sic]. (David, Experiment 5, Reflection)*

> *I would have liked more time to work on the lab and understand the material. I think we rushed through and lost some of the learning. (Blake, Experiment 4 Reflection)*

Students in all four cases experienced at least one experiment that took longer than the scheduled two hours to complete. Several students specifically stated that the length of the experiment hindered their learning.

A second aspect of the laboratory could have hindered students' learning: the type of instructions provided for each laboratory experiment. The instructions were presented in a "cookbook" style: each step was specified explicitly for students to follow. Students in all four cases commented about the instructions. For example,

> *I think more theory should be put into lab sessions. Instead of just having us go through the motion and finishing the lab report. (Dawson, Focus Group)*

> *As I was performing the lab, I did not really understand what I was doing, but was just following the instructions and gathering data. (Abby, Experiment 4 Reflection)*

The comments from Abby and Dawson are all representative examples from students in each case commenting on how they just followed instructions. While some students also commented that they found the instructions were helpful, it is unclear if they achieved the learning objectives of the laboratory experiment or just completed each step without understanding what they were doing or why each step was completed. Students described the latter experience in the comments above.

Students in the treatment and baseline groups had similar ranges of feelings

Students in all four cases experienced a wide range of feelings throughout the semester. They expressed both strong positive feelings such as excitement and happiness, and strong negative feelings such as confusion and frustration. The feelings seemed to vary between experiments, but not between cases. The following quotations illustrate this variation of feelings. Examples of positive feelings are as follows:

> *I think I particularly enjoyed this lab because I am very straightforward result-oriented thinker and learner. (Diane, Experiment 2 Reflection)*

> *...we again used equipment and models to prove what we already knew was true, which I find very fascinating. (Albert, Experiment 2 Reflection)*

Other students had similar comments about feelings in experiment 2 reflections. Students may have reacted positively to experiment 2 because they completed the experiment within the allotted two hours, and they connected the experiment to the lecture material on Laplace transforms. Similarly, in all four cases, students responded positively to experiment 6. For example,

> *I thought this lab was a very enjoyable lab and it was a good capstone lab for the course. (Carl, Experiment 6 Reflection)*

In experiment 6, students were able to make connections between the experiments and lecture. These connections built upon the evidence of learning presented in the previous section. Most students were also able to complete this assignment within the allotted two hours. Unfortunately, negative feelings were also common in the surveys and reflections. These negative feelings can also affect the students' motivation for learning in this experiment. For example,

> *It was especially frustrating because it was hard to see patterns in change in the systems as we changed the controls. (Clare, Experiment 5 Reflection)*

As mentioned with the positive comments on experiment 5, negative comments like these tended to dominate the topics in reflections. Clare mentioned confusion about how to adjust the gain values and understand the impact on the output. Clare's confusion is unfortunate because understanding how to adjust gains to get a desired response is the main learning objective of experiment 5. Regrettably, the objectives of each experiment were not consistently communicated to students in any case. In the fall cases, students stated some negative feelings about the whole laboratory experience. For example,

> *I felt like this stuff was way over my head the entire time (Cliff, Survey)*

> *The overall lab experience was frustrating and confusing. It felt like blindly following instructions a lot of the time. (August, Survey)*

Both Cliff and August mentioned negative reactions toward the laboratory experience in the survey and unfortunately, these are representative comments from a few students in each of the fall cases. There were not enough survey responses from the spring cases to understand the overall feelings toward the laboratory.

Limitations

There are several limitations in this study. It covered only one academic year, one program, and one school. The concept inventory test and the survey had a smaller sample size because students volunteered to take both the concept inventory and survey during the last lecture of the semester. Only four students took the survey and concept inventory in the spring. The sample size of completed surveys was also small, just over the typical minimum 10:1 ratio of samples to factors for exploratory factor analysis (Costello and Osborne 2005). The number of consenting participants in the spring was also close to the minimum number of samples for a student t-test (de Winter 2013). However, the sample size in the fall was sufficient to detect a letter grade difference between each group on each test.

The teaching assistants (TAs) changed between the semesters. The spring treatment case had two TAs and the other three cases each had one TA. The TAs brought different experiences into the laboratory. For example, one TA had taken GE 320 as an undergraduate student, and his research was related to controls, whereas another TA had never taken a controls course prior to leading laboratory sessions in GE 320.

In addition, the TAs did not consistently follow the grading rubrics. One of the TAs did not follow the grading rubric for laboratory 6, so we regraded reports from his section prior to analysis to ensure consistency between sections.

Unfortunately, not all of the data we planned to collect were gathered. We were not able to observe the laboratory sections in the spring, so there is no data to explain the technical errors and excessive time spent using the laboratory kit in the spring semester. Not all of the graded laboratory reports were legibly scanned, and some reports were not scanned at all, so some data were lost.

Even though the students were told that their laboratory reflections would not be graded, the reflections were still turned into the TAs who were responsible for grading. Therefore, some reflections might not have been the complete picture of the experience. The students were told that only the research team would see the data from the focus groups and surveys. The audience might have influenced the responses provided.

We did not use a specific theory to inform the design of the survey or other data collected in this study. Therefore, the breadth or depth of the data in some areas may not be sufficient for a valid interpretation. For example, we focused on the equipment and assignments in the development of the instruments for this study. As a result, the survey and focus groups did not include any specific questions about the TAs, who might have affected the students' laboratory experiences.

DISCUSSION

In this study, we sought to answer three questions. (1) Can students using a portable kit achieve the same learning objectives as students using traditional equipment? (2) Do students' perceptions of their understanding of laboratory concepts differ based on the type of equipment used? (3) Does the student experience differ based on the type of equipment used? Based on the data collected we saw little to no difference in student learning or the student experience based on the type of equipment they used. Based on the exam and concept inventory scores students using both types of equipment achieved the learning objectives at the same level. Students' responses in the surveys and laboratory reflections indicated that the laboratory experiences were about the same for both types of equipment, except factor B3. Factor B3 included an item about circuits: the students in the baseline group wired circuits to implement the control system during the laboratory, while the treatment group used MATLAB and Simulink to implement the control system. The difference in control system implementation could explain the difference in survey responses as well. In this section, we will explore additional factors that could influence student learning and the overall student experience in the laboratory.

Student learning and assessment

In this study, we explored how to assess what students have learned in the laboratory. Student learning can be assessed and measured in a variety of ways. The most popular graded assessments are exams and quizzes; however, projects and presentations are growing in popularity in STEM classes. Graded assessments in STEM laboratories are usually reports or laboratory notebooks. Some laboratories conduct laboratory practical exams, where each individual student demonstrates skills they learned in the laboratory to an instructor. The instructional staff of GE 320 used a variety of assessments to determine the grade earned by each student. Homework, exams, and laboratory reports (including pre-lab and post-lab exercises) were components of the final GE 320 course grade.

Upon further consideration, exams and concept inventories may not accurately assess what students learned in the laboratory. While some concepts are covered in the laboratory experiments as well as on the exams and concept inventory, there is a significant difference in how these concepts are presented to the student in each context. For example, each item on the exams and the concept inventory have one answer. Each item on the exams and concept inventory test use round numbers and simplified systems to make the equations solvable by hand without a calculator or computer. The systems in the laboratory are neither simple and nor contain round numbers. Moreover, the noise, friction, and tolerances within the real motor cause an inaccurate representation of reality in the mathematical models generated during the laboratory experiments. Therefore, there is not one correct answer. The methods used to find gains in the laboratory do not directly translate back to finding gains on an exam. Some of the skills required to design a control system in a laboratory experiment are different from the skills to create an analytical design of a control system on an exam. Therefore, an in-class exam may not accurately assess what skills were learned during a laboratory experiment. A recent study by Wieman and Holmes (2015) also concluded that exams may not be an accurate measure of what students' achieve in an instructional laboratory.

We suggest that a more accurate assessment of student learning be developed for instructional laboratories. Laboratory practical exams might be an alternative to in-class exams because they specifically cover skills that can only be demonstrated in a laboratory setting. However, practical exams are not common across all STEM laboratories. Laboratory reports and post-lab questions are another form of assessment provided they are individual work.

Student experience

In this study, we have focused on the student experience related to the equipment in a control systems laboratory. We found that as long as the students are able to complete the experiments within the scheduled laboratory period, the equipment does not appear to have a significant impact on the student experience. However, previous studies have also shown that other factors can influence the student experience in a laboratory including the type of instructions, the amount of time to complete the experience, and the instructional staff.

The type of laboratory instructions can vary from unstructured to cookbook style. With unstructured laboratory instructions, students are given high-level instructions or goals, and the detailed steps are left for the students to determine (Wankat and Oreovicz 2015). In contrast, in cookbook style laboratory experiments, students simply follow explicitly stated step-by-step procedures (Wankat and Oreovicz 2015). The instructions in the GE320 laboratory were cookbook style. More than one student commented that there were times when they were blindly following instructions and did not know why they were doing it. Some students also indicated that time pressure caused them to focus on completing the experiment rather than learning. According to Truax (2007), cookbook style instructions promote mimicry over a deep understanding of the material. Since GE320 is an introductory level course, a fully unstructured laboratory might not have had the desired outcome either. Wankat and Oreovicz (2015) suggest a balance between detailed instructions and open-ended experimentation that is appropriate for the level and background of the students.

Demands on a student's time can shift their focus from learning to submitting a correct report on time (Bella 2003). Students in both cases reported running short on time or feeling rushed at the end of the laboratory session. Therefore, the length of the experiment or the duration of the section should be adjusted accordingly to allow all students to complete each experiment within the allotted time.

Instructional staff (i.e., teaching assistants, faculty, and staff) set the tone in the laboratory. Students perceive the environment of a course in a range from supportive to unsupportive (Ambrose et al., 2010). This range was evident in the qualitative data for GE 320. One student commented that one TA was condescending and unhelpful. Several students mentioned that the fall TAs were not available enough to answer questions. Both of these situations contributed to an unsupportive environment. However, not all students agreed on the level of support provided by each TA. One way to improve the environment is to make sure the laboratory TAs hold office hours each week that there is a pre-lab or laboratory report due. Another improvement would be to make sure TAs give short introductory talks at the beginning of each laboratory session and are prepared to answer questions that arise during the experiments.

CONCLUSIONS AND FUTURE WORK

We have shown that a laboratory kit is an acceptable alternative to traditional laboratory equipment for an introductory control systems course. Unlike previous studies that just evaluated students who used an affordable kit, we used a quasi-experiment to compare a group of students using an affordable kit to another group of students that used traditional laboratory equipment. We collected both qualitative and quantitative data to evaluate the achievement of learning objectives and the student experience in the laboratory for both groups of students. The students' achievement of learning objectives, experience, and perceptions of learning do not appear to depend on the type of equipment they use in the laboratory, as long as the equipment allows the students to meet the learning objectives of the laboratory.

The specific laboratory equipment does not seem to affect the overall experience and learning objectives, provided the equipment is functional, properly introduced, and supports the objectives of each experiment. In this study, most of the frustrations with both types of equipment arose when something did not work or the student did not feel comfortable using the equipment.

If the laboratory equipment supports the objectives of the laboratory, then the laboratory experiment design and instructional staff might have a greater impact on the overall students' experiences and their learning than the equipment alone. Experiment design could be improved by using an evidence-based theory, such as experiential learning. Migrating from cookbook style to unstructured laboratory instructions is also supported by experiential learning theory, because students can become passive participants with cookbook style laboratories. Finally, students should be able to connect what was learned in the laboratory back to theories and topics learned during lecture. Instructional staff can impact the students' experience by creating a supportive environment in the laboratory. A supportive environment includes setting clear expectations, providing timely feedback, being available to answer questions, and offering the assistance needed to succeed in the laboratory.

Future research includes the investigation of the use of the laboratory kit in other contexts such as allowing the students to take the kit home or in an online course. Because the control systems concept inventory did not appear to be very reliable, we will consider improvements to the test. In addition, since the current assessments do not seem to accurately measure laboratory learning objectives, we will explore other measures of achievement of learning objectives in laboratories.

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APPENDIX

Likert Survey Items

Note: all Likert survey items had the following choices:

A. Strongly disagree
B. Disagree
C. Agree
D. Strongly agree

1. I am satisfied with the GE320 laboratory.
2. I am satisfied with the laboratory equipment for GE320.
3. The GE320 laboratory covered enough content.
4. The GE320 laboratory assignments challenged me.
5. The GE320 laboratory assignments reinforced topics from lecture.
6. I understood the objectives of the GE320 laboratory.
7. I achieved the objectives of the GE320 laboratory.
8. The GE320 laboratory equipment was easy to use.
9. The GE320 laboratory helped me learn concepts discussed in lecture.
10. The GE320 laboratory equipment was a distraction to learning the concepts from lecture.
11. I learned skills in the GE320 laboratory that I could use in industry.
12. I did not learn anything in the GE320 laboratory.
13. The GE320 laboratory equipment aided my learning of course material.
14. I felt frustrated with the GE320 laboratory equipment in more than half of the laboratory sessions.
15. The GE320 laboratory met my expectations.
16. The GE320 laboratory equipment met my expectations.
17. I would recommend that students use the same equipment I used in future GE320 laboratories.

The GE320 laboratory (this includes the pre-lab questions, experiments, and post-lab questions, but does not include homework assignments or lectures) helped me learn the following topics:

1. Circuits
2. Laplace transforms
3. System identification
4. Types of controls
5. System stability
6. Design of control systems
7. MATLAB and Simulink

8. Design of PID controls
9. Design of lead-lag controls
10. Frequency Response

It was easy to understand how to complete the following tasks with the GE320 laboratory equipment:

Tune the sensors used to measure speed and position of the motor

11. Identify the plant (system) to be controlled using first principles (measuring armature resistance, inductance, etc.)
12. Identify the plant (system) to be controlled using step response
13. Identify the plant (system) to be controlled using frequency response
14. Design various PID controllers
15. Implement PID controllers with the real motor
16. Test the PID controllers with the real motor

Open Ended Survey Questions

1. What did you like best about the laboratory equipment you used? Why?
2. What changes to the laboratory equipment would have improved your laboratory experience? Why?
3. What suggestions to you have for the laboratory instructions? Why?
4. Do you have any other comments about your overall laboratory experience? Why?

Focus Group Questions

1. What are your name, year in college, and current major?
2. Which concepts presented in lecture did the laboratory help you learn? How did the laboratory assignments help?
3. Which concepts presented in lecture did the laboratory not help you learn? How did the laboratory assignments hinder your learning?
4. What aspects of the laboratory equipment were easy or difficult to use?
5. What did you like about the laboratory equipment? Dislike?
6. What would you suggest be changed in the lab? Stay the same?
7. What was your favorite part of the GE320 laboratory? Least favorite?