Assessing an Affordable and Portable Laboratory Kit in an Undergraduate Control Systems Course

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***Abstract*—Lab kits allow students to take home laboratory equipment to complete experiments on their own time. Kits like these can expand access to hands-on experiences for online courses and to budget-strapped campuses. Although students like these kits, no previous studies compared student learning outcomes on assignments using these new kits with previous laboratory equipment. During the 2014-2015 academic year, we conducted a quasi-experiment to compare students' achievement of learning outcomes. Half of the laboratory sections in each semester used the existing equipment, while the other sections used the new kit. The objectives of the laboratory assignments were the same and the instructions were kept as close as possible between the two groups.**

I. INTRODUCTION

Laboratory experiences help link theory to practice for undergraduate students [1]. More specifically, [2]–[4] each describe the importance of laboratory experiences in control systems courses, despite challenges such as budget constraints, space limitations, class size, and limited teaching resources [3], [5]–[7]. Providing laboratory experiences to off-campus students is a new consideration with the rising popularity of online courses [2], [8], [9].

A. Background

In a control systems laboratory, students typically learn the following skills: building the system, modeling and analyzing the system, developing a controller to meet performance requirements, simulating the controller and system, observing the physical system, collecting the data, and using the data to improve the system model or control tuning [2], [3], [7]. Although [10] 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 have been identified to meet these skills for controls laboratory experiences [4], [11]. Not only is it straightforward to control the position a DC motor with a proportional-integral-derivative (PID) control [11], a DC motor setup can be expanded to create more complex setups like the inverted pendulum [4].

Lab kits have become popular as the cost of the required hardware has decreased [12]. The contents of each kit vary based on the learning objectives of the course and can be assembled by the instructor [5], [12], adapted from an existing kit [13] or purchased as a complete kit such as Lego Mindstorms NXT [14], [15]. With a lab kit, students can take home laboratory equipment and complete experiments on their own time [12], [13].

The literature includes examples of lab kits that are similar in cost but not used in control systems courses. The Arduino prototyping kit described in [12] costs about $95 and was designed for a multidisciplinary course on perception, light, and semiconductors. The Mobile Studio IOBoard described in [16] has multiple versions ranging in price from $80–$130; it is primarily used in undergraduate circuits courses.

Additionally, 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 [5]. The SEAL System kit costs about $100 plus $179 for a myDAQ from National Instruments [5], [17]. The MESAbox uses an Arduino and costs approximately $180 [13]. 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. The DC motor control equipment detailed in [4] includes a motor, gearbox, encoder, and $80 of hardware components to build a non-portable kit for approximate total of $400 [4], [18].

End-of-semester satisfaction surveys show these kits have been well received by students [5], [7], [12]. However, these studies do not present data to show whether students achieve the intended learning outcomes with these kits. [4], [13] presented student ratings of their own proficiency on learning outcomes before and after taking the class, but there were no direct measures.

B. Purpose

In this study, we aim to replace the basic functionality of an introductory control systems laboratory with an affordable kit. The target budget for the kit is $100 because this approximates the cost of other affordable kits and engineering textbooks [12], [16]. Once the kit was built, we sought to

answer the question: Can an affordable kit achieve the same learning outcomes as traditional equipment? To evaluate the effectiveness of the new kit, we conducted a quasi-experiment during the 2014-2015 academic year. This paper presents the initial analysis of the quantitative data collected to compare student learning outcomes between the two groups.

II. METHODS

A. Context of the Study

GE 320, Control Systems, is the first of two required control systems courses for all General Engineering majors at the University of Illinois at Urbana-Champaign. The course topics include Laplace transforms, linear mechanical and electrical system modeling, transfer functions, system stability, and feedback control design to specifications. The prerequisite courses for GE 320 are Introductory Dynamics and Intro Differential Equations. Additionally, GE 320 students must have completed or be concurrently enrolled in Analog Circuits and Systems. Most students take GE 320 course 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 concurrent laboratory sections. In the spring of 2015, 33 students enrolled in the lecture and one of four concurrent laboratory sections. Half of the laboratory sections used the existing equipment (comparison group) and the other sections used the new kit (treatment group). The authors were not involved in teaching the course during the study.

During the 16-week semester, each student participated in 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 [19]. The last experiment repeats system identification and control design on a new system. Students worked in groups of two (or three if necessary) completed the experiments. However, they submitted individual answers to pre-lab and post-lab questions as well as two-page laboratory reports.

B. Equipment

The new kit designed for GE 320 consisted of a Raspberry Pi (a single board computer that is about the size of a deck of cards), DC motor, a 3D printed stand, and the associated sensors. It cost about $130. A photo of the kit appears in Fig. 2. The existing equipment included an analog computer, DC motor, sensors, oscilloscope, function generator, and multimeter, together costing about $15,000 per station [20]. A photo of the existing equipment appears in Fig. 1.

Even though the kit was designed to be portable, the department purchased six kits for students to use in the laboratory under the same conditions as the existing non-portable equipment used in the course. The objectives of the laboratory experiments were the same and the instructions were kept as close as possible between the two types of equipment.

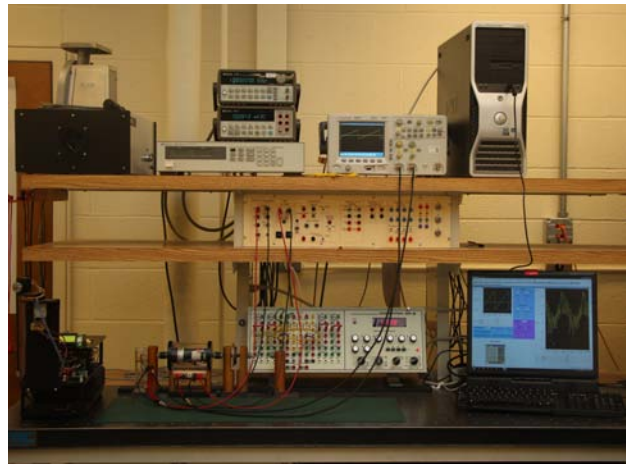

Fig. 1. Existing Equipment

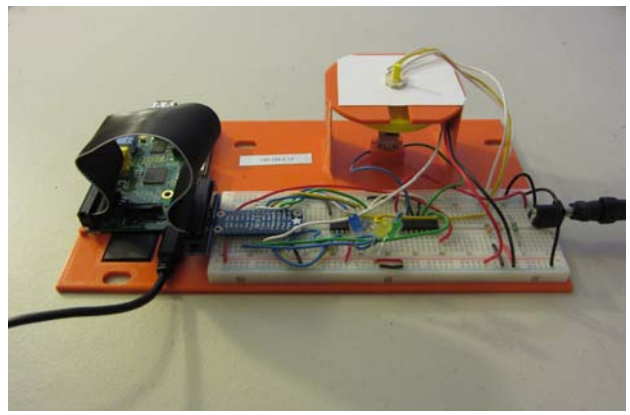

Fig. 2. New Kit

C. Procedure

Quantitative and qualitative data were collected each semester to compare student learning outcomes. The quantitative data included exam scores, laboratory report scores, concept inventory scores, and answers to Likert scale questions on the end-of-semester satisfaction survey. The concept-inventory test is a multiple-choice test constructed by drawing questions from a test that was previously developed to assess students' knowledge about control systems by [21] for mechanical and mechatronics students. Consequently, the original test included questions only about mechanical systems. Students in GE 320 study both mechanical and electrical systems during lecture, but emphasis is placed on electrical systems. We replaced the last question with an equivalent electrical circuit question to ensure a balance between mechanical and electrical systems. A faculty member who has taught GE 320 reviewed the test to ensure the questions were suitable. Student volunteers completed the concept-inventory test and survey on the last day of lecture.

The qualitative data include laboratory observation, student reflections from their individual laboratory reports, and open-ended questions on the satisfaction survey. The analysis of

TABLE I
FALL 2014 GROUP DEMOGRAPHICS

		Treatment	Comparison
Gender	Male	16	19
	Female	10	8
Class Standing	Junior	13	13
	Senior	12	11
	Other	1	3
Exchange student	No	95%	82%
	Yes	5%	18%
GPA	Average	3.4	3.3

qualitative data is still on going.

III. PRELIMINARY RESULTS

Table I presents the demographic characteristics of the students in the fall of 2014. Exchange student status and GPA, on a four-point scale, were self-reported. Gender and class standing were calculated from the course roster. Each group has similar demographics and is representative of the overall General Engineering program.

We investigated whether students would achieve the same learning objectives with both types of equipment. In particular, we tested whether the two groups differed in their exam and concept inventory scores.

We started the quantitative analysis of fall semester data by calculating descriptive statistics and plotting the data in histograms. These statistics are presented in Table II. The histograms for each exam are shown in Fig. 3-5 and for the concept inventory in Fig. 6. Then we checked the data for outliers using Grubb's test and normality using the Jarque-Bera test. Exam 1 and the final exam each had one low scoring outlier in the comparison group. Once the outliers were removed, the data from each group and exam were approximately normal.

Finally, we ran a two-sample, two-tailed, t-test for each exam. An $\alpha = 0.05$ was used in each test. Based on this test we do not reject the hypothesis. The Cohen's d effect size and power were also calculated with each test; see Table II. Since the power is very low, additional data will be collected in the spring semester. However, only the concept inventory test will be the same for both semesters.

Even though low scores are expected on concept inventory tests, we checked for other factors that could have influenced the outcome. However, there was no correlation between the time spent taking the concept inventory and the score and very low correlation between the self-reported GPA and the concept inventory score.

IV. CONCLUSIONS AND FUTURE WORK

The initial quantitative analysis of the fall semester data indicates that achievement of the learning outcomes with both types of equipment are the same. However, the power of the tests is low, so more data was collected in the spring semester.

TABLE II
FALL 2014 EXAM AND CONCEPT INVENTORY DESCRIPTIVE STATISTICS

	Treatment			Comparison			Cohen's	
	n	*M*	*SD*	*n*	*M*	*SD*	*d*	Power
Exam 1	24	79.4	14.2	26	82.0	11.6	0.2	0.1
Exam 2	26	83.0	9.4	27	84.3	7.7	0.1	0.1
Final Exam	26	86.1	7.1	25	83.2	7.7	0.4	0.3
CI	16	32.6	11.6	19	35.4	12.0	0.2	0.1

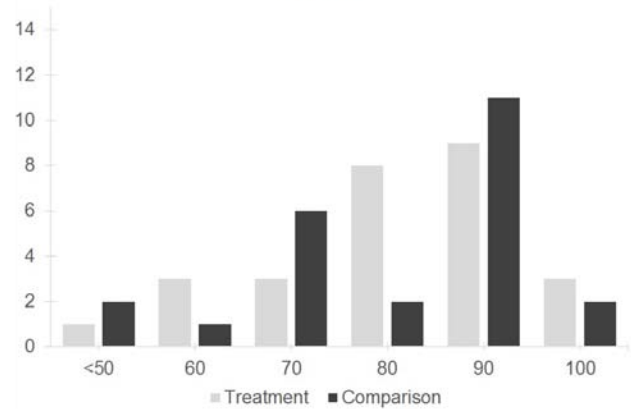

Fig. 3. Exam 1 Results

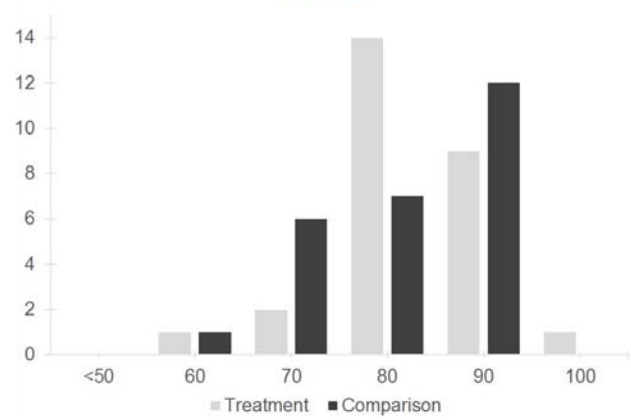

Fig. 4. Exam 2 Results

Complete analysis of all of the quantitative and qualitative data is still ongoing.

Future quantitative analysis includes the survey responses and laboratory reports. Select pre-lab and post-lab questions will also be analyzed using a paired t-test. Qualitative data sources will be coded for themes related to the equipment and overall laboratory experience.

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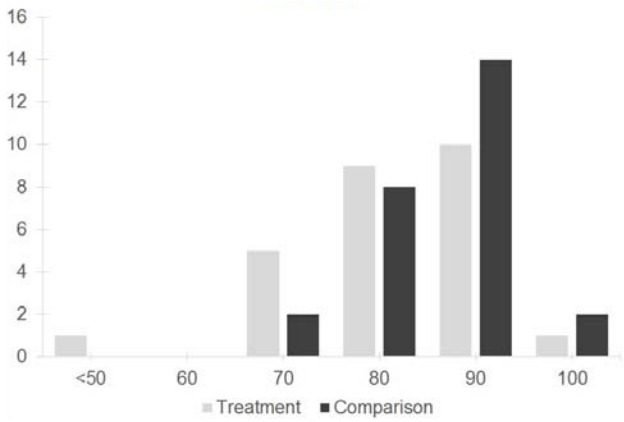

Fig. 5. Final Exam Results

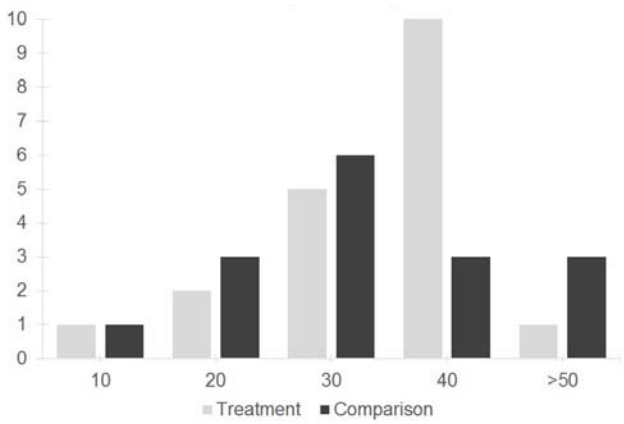

Fig. 6. Concept Inventory Results

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