AC 2012-3864: SCIENCE AND ENGINEERING ACTIVE LEARNING (SEAL) SYSTEM: A NOVEL APPROACH TO CONTROLS LABORATORIES

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Science and Engineering Active Learning System: A Novel Approach to Controls Laboratories

Introduction

Student access to laboratory experiments is critical in science and engineering curricula. Universities invest tremendous amounts of funding and energy in establishing and maintaining traditional labs for physics, engineering, circuit design, controls, and other fields. Along with the high cost associated with such labs, there are other problems inherent in this practice. First, due to the expense of individual platforms, they must be shared by a large number of students. This poses a significant scheduling burden for administrators and students alike. Second, students must perform experiments in a laboratory setting, which is highly stressful and not conducive to learning.

In response to these issues, the Electrical Engineering Department at UCLA recently performed a significant overhaul of its electronic circuits laboratories. Traditional laboratory experiments using oscilloscopes and signal generators were replaced with take-home projects wherein students designed and implemented a series of audio signal conditioning circuits. Students were provided with prototyping boards, circuit components, and myDAQ portable data acquisition devices from National Instruments which served as oscilloscopes and signal generators. These components enabled students to work at home while providing all the capabilities of a traditional laboratory.

The tremendous success of these changes has motivated improvements in other laboratory courses. In particular, electrical engineering students in feedback control courses at UCLA previously had limited access to hands-on control platforms. Thus, it became a major research imperative to extend the concept of low-cost, take-home devices to controls courses. In this paper, we present the culmination of these efforts: the Science and Engineering Active Learning (SEAL) System, a highly versatile, portable inverted pendulum control platform that is sufficiently inexpensive to provide it to individual students or very small groups of students. The bill of materials for the system is roughly $100, and it fits easily inside a 9 $^{3}/_{8}$ x 8 x 6 $^{7}/_{8}$ -inch carrying case.

The objective of this system is to enable end-to-end student implementation of a variety of control systems. This includes physical assembly, implementation of electromechanical systems, sophisticated system identification, design of control algorithms, and experimental verification. This system was adopted by the UCLA Electrical Engineering Introduction to Feedback Controls course in the winter 2011 quarter. This initial adoption consisted of 140 students sharing 50 SEAL platforms.

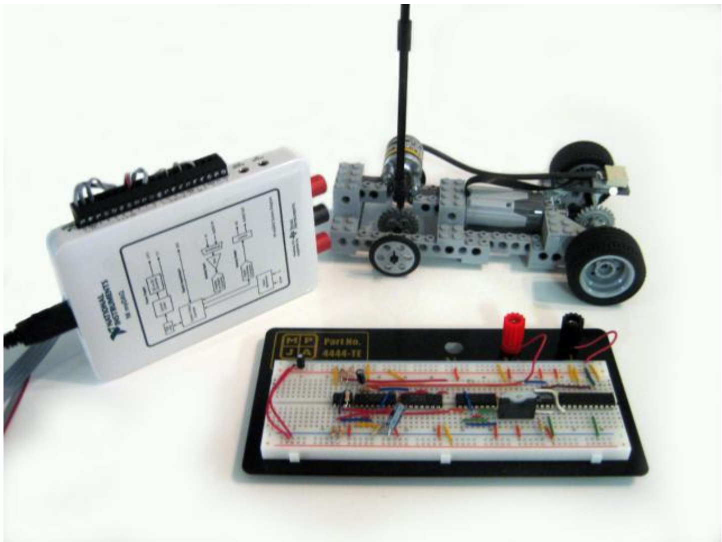


Figure 1: The SEAL inverted pendulum system, consisting of a LEGO car, electronic systems implemented on a protoboard, and a National Instruments myDAQ data acquisition device.

Platform Description

The SEAL platform, shown in Figure 1, consists of a car assembled primarily from LEGO components and novel electronic systems implemented by students on a prototype board, both of which interface with an NI myDAQ data acquisition device. We note here that the myDAQ device is not included in the SEAL platform. The method used at UCLA, which is typical of a number of universities that use similar devices, is that myDAQ units are lent to students as required for circuits laboratories or for use with the SEAL platform. Alternatively, some schools require students to purchase such devices during their freshman year and use them throughout the curriculum for a number of applications.

The parts for the car are purchased from LEGO in modular, pre-sorted bags, and they are provided to students in an unassembled state. The first assignment is to assemble it and become familiar with its components, which include a DC motor and 360 count-per-revolution (CPR) optical encoder. A detailed instruction manual is provided that guides the student through this process, which takes roughly 20 minutes. An example page from this manual is shown in Figure 2.

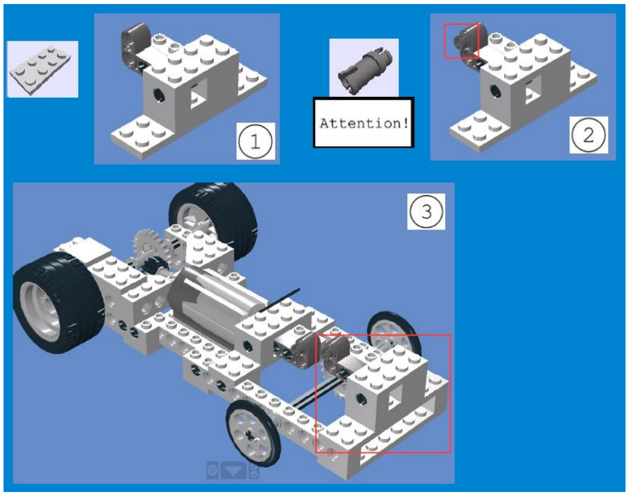


Figure 2: A page taken from the assembly guide detailing the construction of the SEAL system.

As described above, the sensor provided with the SEAL platform is a 360 CPR optical encoder. By changing a single LEGO part, this encoder can be configured to measure either rotation of the car's axle, and thereby the car's position, or of the inverted pendulum. These two configurations are shown in Figure 3. This capability enables tremendous flexibility in designing controls assignments, as instructors may begin with basic car position control, which can be readily achieved by proportional control and improved by adding a derivative term, and then move toward the more difficult problem of inverted pendulum stabilization.

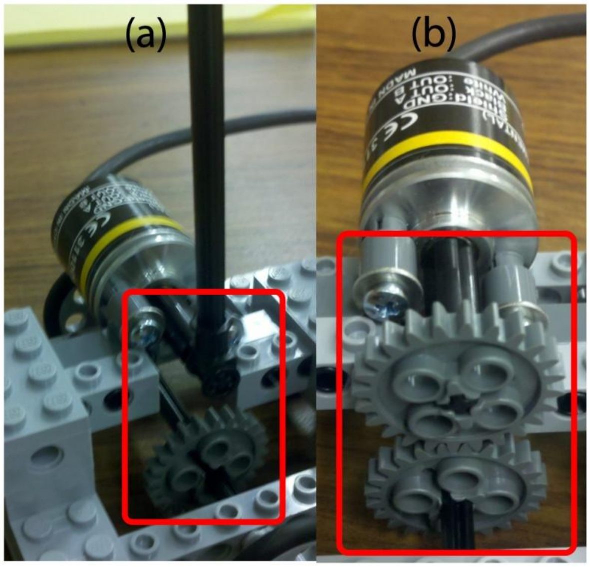
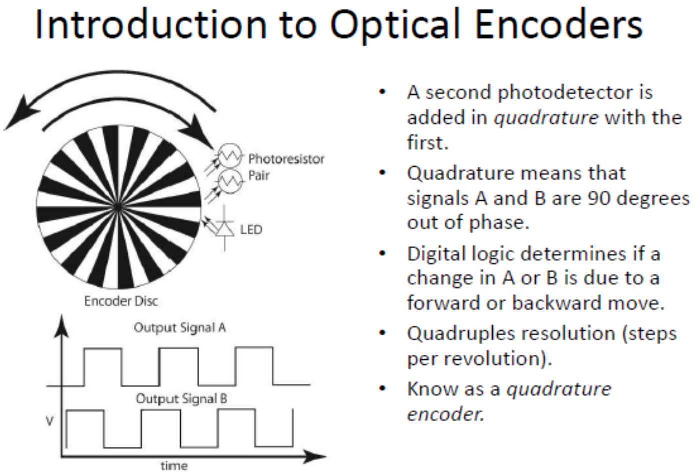


Figure 3: The dual functionality of the optical encoder: In (a), the inverted pendulum is mounted directly on the encoder's output shaft. In (b), the encoder shaft is equipped with a gear that meshes with another gear mounted on the car's front axle.

The electronic systems of the SEAL platform are also provided in an unassembled state. The second student assignment is to implement the SEAL electronic systems on a prototype board using components provided in the kit. These systems include an optical encoder interface, a motor driver, and an electrical kill-switch, which stops the car if incorrect voltage levels are applied. Students are provided with assembly instructions, in which each of these sub-systems is presented as a modular element. Each module begins with an introduction that describes the theory and principles of operation of the corresponding sub-system. Thereafter, step-by-step assembly instructions are provided that walk students through the physical implementation of the system.

As an example, the first sub-system considered is the interface between the optical encoder and the National Instruments data acquisition device. In this module, the operating principles of an optical encoder are described: the use of LED/photoresitor pairs to detect markings on a revolving disc is presented; the need for two photoresistors acting in quadrature is explained; and a digital truth table for quadrature decoding is described. Thereafter, the integrated circuits required for the interface are introduced. Finally, step-by-step circuit assembly instructions are provided. An example page describing optical quadrature encoders is shown in Figure 4, and an example page from the corresponding step-by-step circuit assembly documentation is shown in Figure 5.



Introduction to Optical Encoders

- A second photodetector is added in *quadrature* with the first.
- Quadrature means that signals A and B are 90 degrees out of phase.
- Digital logic determines if a change in A or B is due to a forward or backward move.
- Quadruples resolution (steps per revolution).
- Know as a *quadrature encoder.*

Figure 4: An example page from the circuit instruction manual describing the principles of operation of quadrature optical encoders.

It is important to note here that these inverted pendulum kits were not intended for use in a circuits or mechatronics laboratory, but rather for a controls course. Providing students with hands-on experience with critical motor control and sensor interface technology perhaps does not significantly impact their learning of control theory; such advantages are more concrete in the controls exercises in subsequent weeks. However, this hands-on experience with critical components such as H-bridges, Pulse-Width Modulation, optical encoders, and digital logic gates provides immense educational benefits across the engineering spectrum. End-of-course surveys indicate that students appreciated these “fringe” benefits tremendously and that end-to-end implementation of an electromechanical control system was a very rewarding experience.

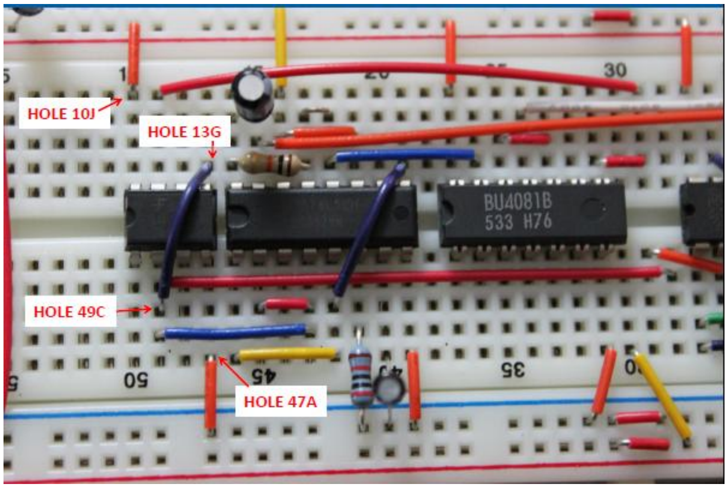


Figure 5: An example page from the step-by-step circuit assembly guide detailing insertion of wires into labeled locations on the prototype board.

Controls curriculum supported by the SEAL system

An extensive suite of software components has been generated for use with the SEAL system. These elements, written in National Instrument’s LabVIEW software, are intended to provide all the functionalities of traditional, lab-scale inverted pendulum systems. This software is highly modular in nature, and instructors can select which elements to include in the curriculum. During the adoption of the SEAL system at UCLA, students were provided with executable LabVIEW elements rather than source code. Alternatively, other adopters have provided source code or have required students to generate code on their own.

Each laboratory module is supported by a stand-alone assignment description which provides all control theory required before detailing the assignment. Roughly, the curriculum can be divided into the following categories: (1) System Identification, (2) Control Design Tools, and (3) Experimental Verification of Controls.

System Identification

For any control design beyond manual PID tuning, some sort of plant model is typically required. Such a model can be generated through a number of methods, including analytical or empirical evaluation of behavior. The SEAL system incorporates all of these methods in its System Identification capabilities. First, an analytical derivation of car dynamics is provided. Thereafter, a frequency sweep of the actuator systems is performed. This yields Bode plots of amplitude and phase, from which a linear model can be generated. An example plot is shown in Figure 6. Performing analytical and empirical system identification enables students to experience the advantages and shortcomings associated with each approach; the mathematical rigor of analytical derivations show how differential equations and Laplace transforms can be used to generate accurate system models. However, measuring system parameters such as motor properties, moments, inertia, and friction can be quite difficult. On the other hand, empirical frequency sweep methods provide students with new insight and a more physically intuitive understanding of frequency response and Bode plots. For example, the frequency sweep clearly demonstrates why physical systems show a decrease in excitation amplitude at high frequencies and why phase lag accompanies such decreases.

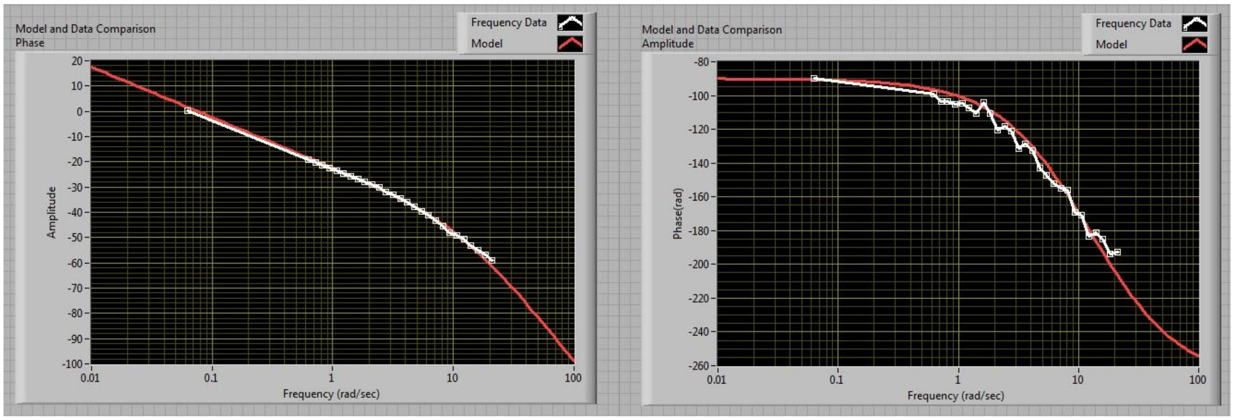


Figure 6: Bode plots showing data from frequency response of actuator systems as well as the response of the linear model generated from the data.

In order to model the dynamics of the pendulum, its period of oscillation is found empirically by suspending it in a non-inverted manner and measuring the period. From these measurements, analytical methods can be used to generate a linearized model of the inverted pendulum.

Control Design Tools

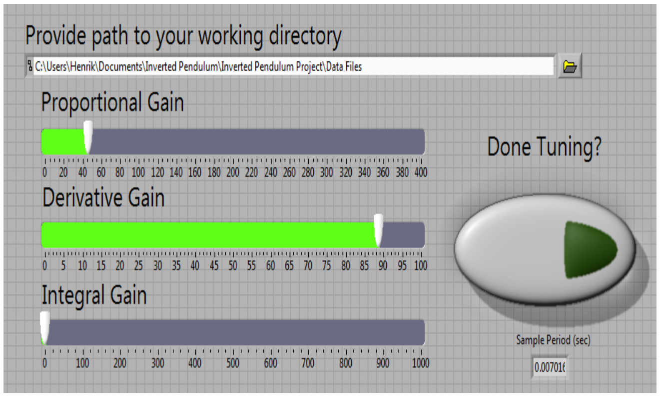
A useful set of LabVIEW control design tools has been generated for the SEAL system. The first of these enables students to manually tune a PID car position controller in simulation before verifying its performance. In this software, a plotted step response resulting from a particular set of control coefficients changes as these coefficients are changed manually. LabVIEW control panels are particularly useful here.

A second control design program allows students to visualize the behavior of a zero-pole-gain controller in real-time while tuning its parameters. This program can be used for both car position control and inverted pendulum stabilization.

One of the primary objectives in designing the SEAL system was to ensure that it could be easily adopted by any instructor, regardless of how they choose to teach controls. A number of control design and analysis software suites are available, and it is critical that SEAL be compatible with each of them. Therefore, all of the LabVIEW software generated for the SEAL system provides interfaces both with other LabVIEW modules and with outside software elements via straightforward text files.

Control Verification Software

A primary objective of the SEAL system was to provide students with a testbed on which to develop and empirically verify control algorithms. Thus, software elements are required that enable such experimentation. The first of these is a PID tuning exercise which allows students to manually tune the three associated control coefficients and perform car position step responses to determine plant response. A screenshot of the manual tuning interface is shown in Figure 7, and a resulting step response as performed on a physical SEAL system is shown in Figure 8.



Provide path to your working directory: C:\Users\Henrik\Documents\Inverted Pendulum\Inverted Pendulum Project\Data Files

Sample Period (sec): 0.00701

Figure 7: A screenshot of the manual PID tuning interface generated for the SEAL system.

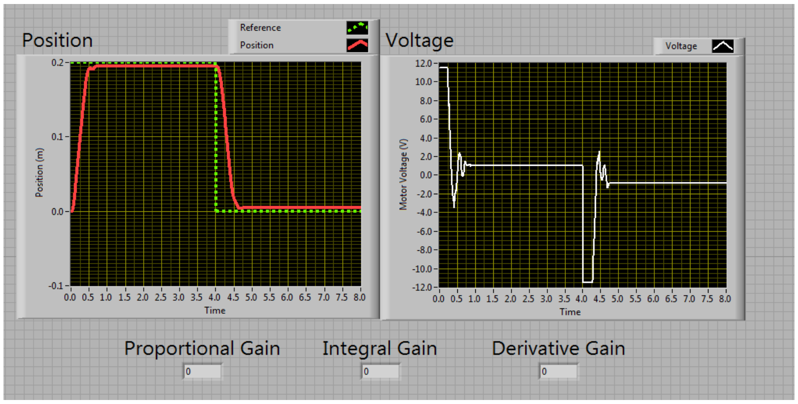


Figure 8: Step response showing the behavior of a physical SEAL system in response to a PID controller. Car position is shown at left, and motor voltage, or control effort, is shown at right.

One of the points of emphasis of the above exercise is that manual, "guess-and-check" PID tuning can be quite difficult and tiresome, and that engineers are often better served using more advanced control techniques. In a subsequent assignment, students were tasked with designing lead lag compensation for car position control using root locus and frequency design methods. To experimentally verify controller performance, an application was generated wherein the car performs a step response experiment using the control algorithm in question, and the resulting position trajectory is shown alongside expected behavior. An example plot is shown in Figure ***9***.

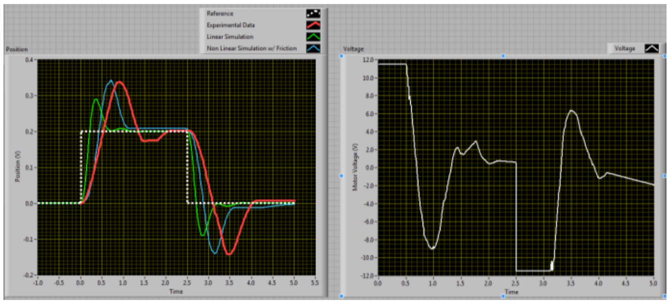


Figure 9: Step response plots for lead-lag compensation of car position. At left, the experimentally observed trajectory is shown alongside expected results based on linear and non-linear models. At right, the applied motor voltage is shown.

To further demonstrate the steady-state benefits of applying lag control, students also generated ramp responses for lead (Figure 10) and lead-lag (Figure 11) compensation. Similar software exists that experimentally verifies inverted pendulum stabilization based on student-designed controllers.

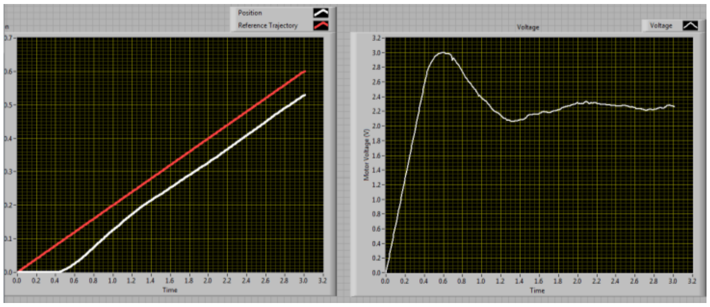


Figure 10: Ramp response of a lead compensator demonstrating large steady state error.

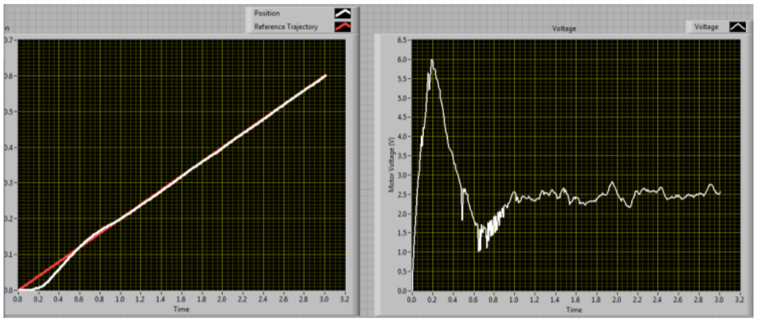


Figure 11: Ramp response of lead lag compensation demonstrating near-zero steady state error.

Large scale adoption

The SEAL system was first adopted in the Winter 2011 Introduction to Feedback Control Course in the UCLA Electrical Engineering Department. This course consisted of 140 students sharing 50 SEAL platforms in groups of 2-3 students. All 50 inverted pendulum kits are contained in the three cardboard boxes shown in Figure 12. Each group was assigned a weekly meeting time, wherein they met with a teaching assistant to verify completion of that week's assignment. During these meetings, the students are also quizzed orally to ensure proper understanding of the topics covered in the assignment.

Figure 12: All 50 inverted pendulum kits distributed during winter quarter 2011 fit in three cardboard boxes, shown here next to an author for scale.

Upon completion of the course, students were asked to rate their experiences using a 5-point Likert scale on: learning, development of design skills, development of hands-on skills with electronics, engagement in course material, increased effort, and student interaction with instructors and other students. For each of these categories, students were asked to rate the effectiveness of the course relative to that of other engineering courses. The 5-point Likert scale was as follows: 1- Much less effective; 2- Less effective; 3- Similar; 4- More effective; 5- Much more effective. Additionally, students were provided with space for write-in comments. A total of 103 surveys were collected. The results are summarized in Table 1.

Table 1: Summary of student end-of-course evaluations. (*)- relative to other engineering courses.

	Much less effective*	Less effective*	Similar*	More effective*	Much more effective*
Learning of course material	0	1	12	**56**	34
Development of design skills	1	2	18	**55**	27
Development of hands-on skills with “electronics”	0	14	20	**48**	21

Engagement in course content	0	1	13	**52**	37
Increased effort in learning course content	0	1	25	**57**	19
Interaction with the instructor/TA	0	1	18	39	**44**
Interaction with other students	1	0	34	**38**	27

Perceived learning of Course Material

Students were asked to evaluate their perceived learning of course material relative to other courses on a 5-point Likert scale. The mean response was 4.19, with a standard deviation of 0.67. One student wrote that the SEAL system was “extremely helpful in overall understanding,” and that the lack of “hands-on experience” in other classes makes that material “much less memorable.” Another stated that he “would never have understood how PID works” if he was “just taught the theory.” Overall, these results support our beliefs that tangible, hands-on experience is critical in generating deeper understanding and achieving learning objectives.

Perceived development of design skills

When asked to rate their perceived learning of design skills, students reported a mean score of 4.01, with a standard deviation of 0.78. One student wrote that she appreciated the opportunity to “actually design something on hand, not just theoretically,” while another complained that “other engineering courses don’t even have any design assignments.” We note here that a handful of students felt that some assignments had provided too much step-by-step description, thereby reducing the amount of actual design work that they were able to complete. There is a critical trade-off between providing rich, design-related assignments and a non-intimidating, user-friendly experience. In subsequent quarters, we have tried to shift the balance towards allowing students more design freedom and providing a less restrictive assignment framework. This has met mixed results, as some have complained about the relative lack of step-by-step support.

Development of hands-on-skills with electronics

Despite being considered a “fringe” benefit relative to control and design related learning objectives, students reported a fairly high mean score of 3.74 (SD = 0.94) when asked to rate their perceived development of practical hands-on skills with electronics. This question referred primarily to the experience of assembling the various circuits on the prototype board. In order to reduce confusion as well as the number of destroyed electronic components, this assignment provided extensive step-by-step instructions. Thus, some students were frustrated with the lack of design elements here. However, the mean score is still well above average. One student described perfectly a primary objective of including this hands-on circuit work in the project: “In normal classes, we don't get the chance to play with the components we study. This hands-on approach made it much more enjoyable.”

Engagement in course material

Students were asked to rate their engagement in course content relative to other classes. The mean score was 4.21 (SD = 0.69), and written responses indicate that the SEAL platform was tremendously effective in motivating students, providing meaningful hands-on experience, and generating an increased level of interest. One student wrote that “an application-based component helped motivate” them, while another explained that this was his first class with “first-hand experience” making it “a lot more interesting.” Wrote another student: “seeing direct application of the theory in class was awesome and definitely made the class much more interesting rather than just learning theory. Probably one of the funnest [sic] engineering classes I've taken.”

Increased effort

When students were asked to rate their effort in learning course content relative to other courses, the average score was 3.92 (SD = .68). One student wrote: “Much more interested = much more effort!”

Student interaction with instructors and other students

Students were also asked to rate their interaction with the instructor (M = 4.24, SD = 0.77) and other students (M = 3.90, SD = 0.84). Students reported that interaction with their groups was very helpful in understanding difficult concepts.

Conclusion

The overwhelmingly positive student response to the SEAL system argues that low-cost, hands-on experimental platforms should constitute a major component of engineering education. The motivational benefits of carefully-designed laboratory experiments are well-known, and making traditional controls laboratory platforms portable and sufficiently low-cost for take-home use in small groups dramatically extends such benefits.

The benefits of the SEAL platform are not limited to the motivational and educational improvements for students; the potential financial impact for universities could be tremendous. In our initial adoption, consisting of 50 inverted pendulum kits, the bill of materials was roughly $5,000. The price of a single traditional controls laboratory system can be an order of magnitude larger. Further, the lab space and expert supervision required to maintain such systems can become exceedingly expensive. Once the SEAL kits are in the hands of students, they pose little more of a burden to a course administrator than a textbook. Assignments are completed at home, and, as is the case for traditional coursework, the instructor and teaching assistants may be required to answer questions via an online forum or office hours. As is typically the case for traditional coursework, verification of assignment completion can be performed by teaching assistants or graders.

The objective of providing low-cost, take-home educational devices is certainly not limited to controls laboratories. In fact, designing a sufficiently inexpensive and user-friendly inverted pendulum platform that can fit into a container smaller than a shoebox likely presents one of the more difficult problems in providing engineering students with such portable systems. The educational philosophy represented by the SEAL system is readily extensible to a wide variety of courses and laboratories, and pursuing these avenues represents a major ongoing research thrust.