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Using LEGO Kits to Teach Higher Level Problem Solving Skills in System Dynamics: A Case Study

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ABSTRACT

System Dynamics is a required course offered to junior Mechanical Engineering students at Penn State Erie, the Behrend College. It addresses the intercoupling dynamics of a wide range of dynamic systems: including mechanical, electrical, fluid, hydraulic, electromechanical, and biomedical systems. This course is challenging for students due to the abstract nature and advanced mathematics needed to understand the topic. While hands-on experience can be a useful tool in learning the material, the ready-to-use units in the market are costly. This paper explores the applications of using low cost LEGO® MINDSTORMS® NXT kits to help students learn key quantitative skills in Systems Dynamics course. The labs include (1) time response of a first order system and transfer function identification and verification, (2) time response of a second order system, and (3) PD controller design. These lab activities use MATLAB®/Simulink® to study the response of LEGO MINDSTORMS units. Multiple student surveys (before and after each lab, at the end of semester, one semester/year after the completion of course) and multiple learning assessments have been analyzed and have shown that there is an improvement in students' confidence and skills in topics covered by the labs.

Key words: Hands-on experience, mechanical engineering, Systems Dynamics, quantitative, problem solving

INTRODUCTION

System Dynamics is a core undergraduate engineering course that studies complex relationships among various aspects of a system and the behaviors of the system over time [1]. Most undergraduate mechanical engineering programs offer system dynamics, either as one independent course, one course with an associated lab, or as two courses offered in sequence. Currently, System Dynamics is offered as a one-semester junior course by the Department of Mechanical Engineering in the School of Engineering at Penn State Behrend. This course has evolved from a previous course that focused on the design of feedback controllers [4]. It does not have a sequel in the ME curriculum. Unlike most other courses in the ME field, Behrend's System Dynamics course involves the study of several subject areas including mechanical, hydraulic, pneumatic, thermal, electrical, electromechanical, and biological systems. It emphasizes the use of mapping input-output relationships to solve problems. One big challenge of teaching this course is that the complexity of mathematical tools makes the course material abstract, adding difficulty for student understanding [3]. On top of that, because of the breadth of course coverage, it is hard to teach students to think dynamically and holistically [2]. An investigation in current engineering education literature found two approaches to be effective in addressing those challenges, although each has its own drawbacks. Applying real life cases in economy, biology, and information sciences has demonstrated success in teaching systematic thinking, targeting qualitative understanding and analysis [15, 20, 21]. However, it usually takes multiple weeks to complete a case study because the background knowledge is usually foreign to engineering students. Other studies show that hands-on experience was very effective in teaching key quantitative skills in system dynamics [14, 16-19]. Some of these studies used low cost equipment, such as analog circuits [19], haptic paddles [14], or bicycles [18]. It is to be noted, however, successful integration of those hands-on experience required either strong electrical background [19] or customized programming [14] and the duration of the project took a few weeks of the course time [14, 18]. Other hands-on experience was executed through ready-to-use units such as those made by Quanser® [16-17]. Those ready-to-use units in the market are costly. The price per unit typically falls in between four thousand and more than ten thousand dollars. In addition, integrating hands-on experience to the course requires at least five to eight three-hour labs [14] in an eleven-week [16-17] lab course; a schedule that would not work for the current Behrend ME program.

To address our challenges and the curriculum constraints, we had to be creative by taking a "blended" approach based on previous studies. We decided to add the hands-on component to the course to improve students' quantitative skills. But unlike some studies that had up to eight labs, we introduced only three labs to the course without causing major changes in the curriculum. Considering the sustainability of these labs, we adopted budget-friendly LEGO MINDSTORMS education kits. In this paper, we will first give an introduction of the course structure and the rationale to include labs. A description of lab activities, together with that of student surveys and assessments are presented next, followed by the analysis of survey and assessment results. To conclude, we will share the lessons learned as well as suggestions for future practice.

METHOD

The topics of Behrend's System Dynamics course include: system modeling using transfer functions and state space models, stability, nonlinearity, time domain analysis, frequency domain analysis, and Proportional Integral and Derivative (PID) controller design through root locus. Controller design is covered as an application of system dynamics. In this section, we will first discuss the lab equipment and lab activities, then the details of multiple surveys and assessments we used in this course.

LEGO MINDSTORM NXT

LEGO MINDSTORMS NXT education version is a programmable robotics kit including about 400 LEGO pieces, three servomotors, four sensors (ultrasonic, sound, touch, and light), seven connection cables, a USB interface cable, and a NXT Intelligent Brick. The Intelligent Brick is the "brain" of a Mindstorms machine, which can process the sensor data and perform different operations of its servomotors autonomously. Each kit was purchased at less than 400 US dollars [5]. Because of the low cost and its popularity among students, LEGO MINDSTORMS education kits have been used in many undergraduate engineering programs, particularly in computer programming or robotics courses [8-13]. In addition, LEGO MINDSTORMS NXT is also compatible with MATLAB/Simulink through a third party supporter package; a software that had already been introduced and implemented in the present System Dynamics curriculum through lectures and homework assignments. The advantages in cost, versatility, and compatibility with MATLAB/Simulink have made LEGO MINDSTORM NXT a very attractive unit for offering hands-on experience to students.

LEGO Labs

Since Fall 2014, three LEGO labs were introduced in the System Dynamics course in both spring and fall semesters, using 12 education version kits of LEGO MINDSTORMS NXT funded by the Institute of Electrical and Electronics Engineers (IEEE) Control System Society. It now impacts more than 120 students annually. The labs include: (1) time response of a first order system and transfer function identification, (2) time response of a second order system, and (3) PD controller design. These labs were offered using three 50-minute sections of regular lecture time until Fall 2015, and have since been offered using three 75-minute sections.

Lab Hardware setting

The hardware involved in the LEGO labs includes LEGO MINDSTORMS NXT set and a host computer with MATLAB 2014a. The algorithms developed in MATLAB/Simulink can be downloaded to the LEGO NXT brick through a USB cable to operate the servomotors, while the sensor signals are transmitted through Bluetooth back to MATLAB/Simulink in the host computer. Due to the lack of internal Bluetooth capability in the host computer, a USB Bluetooth adaptor (Bluesoleil 2, IVT Co., China) is plugged in the host computer, and a Bluetooth driver is used to set up the Bluetooth communication between MATLAB/Simulink in the host computer and the NXT brick.

The NXT Brick can run up to three servomotors using the 9V battery power. Each servomotor has a sensor (encoder) that can measure the motor's angular position with the resolution of one degree. For these labs the data were recorded at 100 Hz instead of a higher possible rate because of the limitation of the sensor resolution. The voltage provided to the motor could be set through MATLAB/Simulink.

Lab Activities

For each lab, students worked in self-selected groups of 2-3 individuals in two consecutive class periods. Half of the groups worked on the lab during the first class, while the other half of the groups received time off and met during the second class instead. There was a short prelab report regarding the technical analysis of the lab. Students needed to turn in an individual prelab report before participating in the lab. During each lab, students were given a MATLAB/Simulink template algorithm file for the experiment. Each group had a LEGO MINDSTROMS NXT kit to run their experiments. They had to connect all hardware, and adjust some parameters of the template file to run the experiment. After the algorithms were executed, students saved the data of the sensor and analyzed the collected data using MATLAB during or after class, and turned in one copy of lab report per group. The details of each lab are discussed in this section.

Lab 1: First Order System Analysis

The objective of Lab 1 is to study the step response of first order system. In this lab, students used a Simulink file to study the response of the motor angular velocity with a constant power input (i.e. a step input) of two configurations: (1) an unloaded servomotor, and (2) a loaded servomotor with a robotic claw (Fig 1), both which displayed a traditional first order system response to a step function input. The claw subject was constructed using LEGO pieces, simulating a larger mass moment of inertia. The servomotor of LEGO is a standard DC motor, whose relation between the voltage input V_a and the angular velocity ω_m output can be modeled as a standard first order system as shown in Equation 1.

$$G(s) = \frac{a}{\tau s + 1} \tag{1}$$

For this system a is determined by the back emf constant (K_e), while the time response (τ) is a result of the back emf constant, as well as armature winding resistance (R_a), motor torque constant

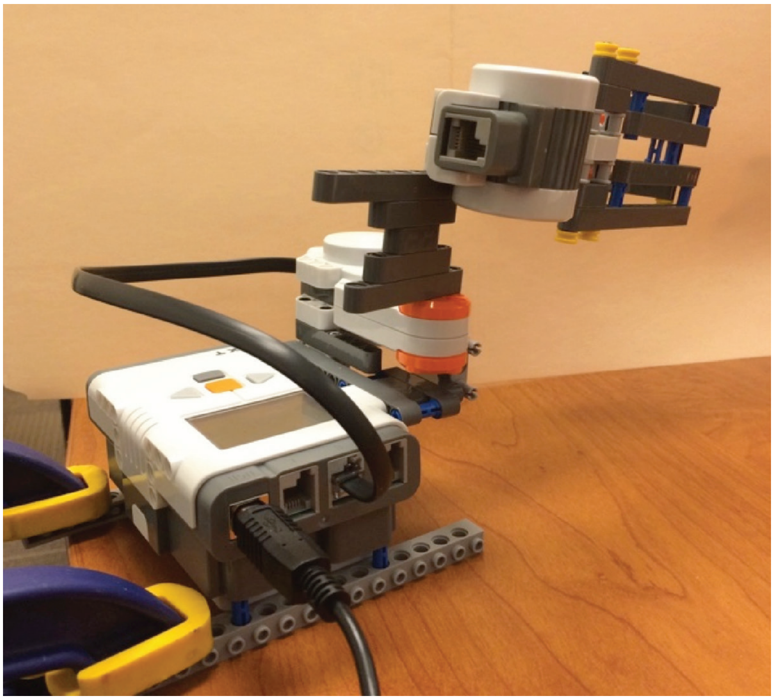

Figure 1. A NXT Brick with robotic claw acting as a load on the motor.

(K_t) and the mass moment of inertia (J_m) on the rotor of the motor.

$$G(s) = \frac{\omega_m(s)}{V_s(s)} = \frac{\frac{1}{k_e}}{\frac{J_m R_a}{K_t K_e} s + 1} \tag{2}$$

By adding the robotic claw in the second configuration, the mass moment of inertia would increase, resulting in a greater value for τ. For the prelab report, students had to compare two first-order systems with different transfer functions, and predict their responses to a given step input. During the lab, after connecting all hardware together, students were to use the provided MATLAB/Simulink file (Fig. 2) to apply voltage as a step function to the motor, and record the angular velocity of the servomotor as a function of time. Using MATLAB to plot the actual trajectory of the motor angular velocity, students should be able to predict the time constant τ, as well as the transfer function of the first order system for the configurations of unloaded and loaded servomotor. For the postlab report, each group was asked to find the transfer function for the unloaded and loaded configurations, and plot a simulated first order response over the lab data for each configuration.

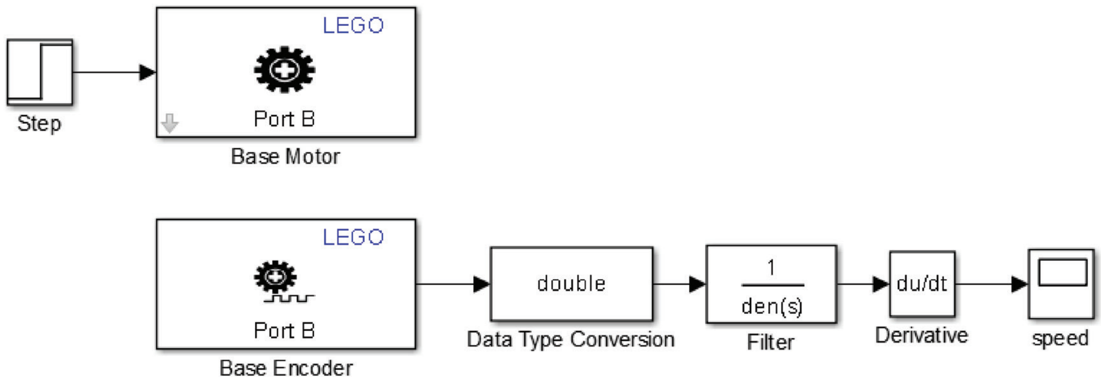

Figure 2. The MATLAB/Simulink file of Lab 1.

Lab 2: Second Order System Analysis

The objective of Lab 2 is to study the step response of an underdamped second order system. In this lab, the MATLAB/Simulink model tracked the position of the motor when given a reference target, in order to show students a standard underdamped second order system response to a step function. For both the second and third lab, a feedback mechanism was introduced (Fig. 3). The motor was put inside a negative feedback loop, which regulated the motor angular position through a controller (G_c) to track a step input reference of 90°. In Lab 2 the controller was a simple proportional controller.

$$G_c = K_p \tag{3}$$

In Lab 2, the controller K_p had the value of 5. This configuration resulted in an underdamped second order relation between the reference input and the angular position output.

$$\frac{\theta(s)}{R(s)} = \frac{aK_p}{\tau s^2 + s + aK_p} \tag{4}$$

Figure 3. The feedback loop representing the logic of Labs 2 and 3.

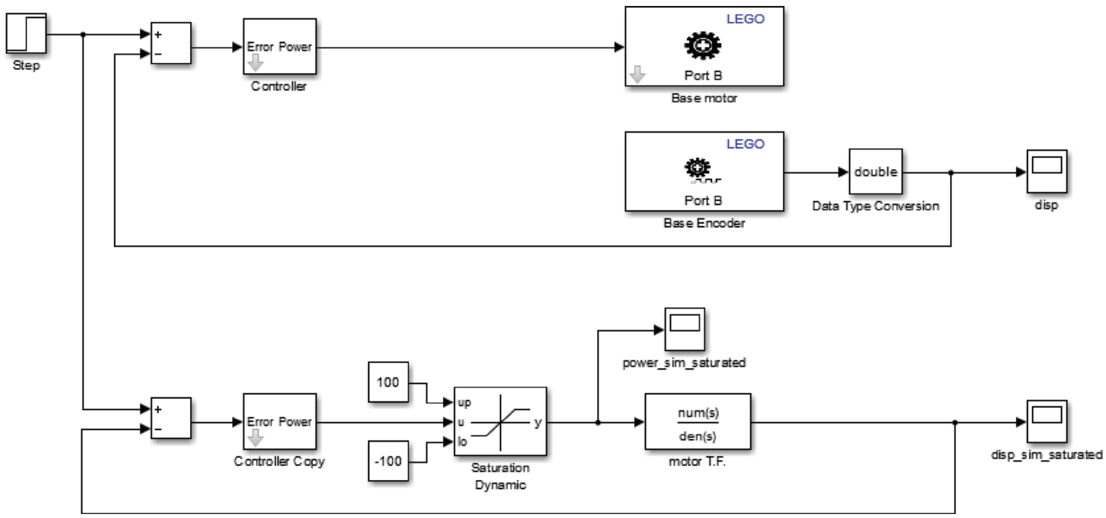

Figure 4. The MATLAB/Simulink file of Labs 2 and 3.

For the prelab, students had to use block diagram algebra and the loaded motor transfer function identified in Lab 1 to derive theoretical transfer function for the second order system, and to predict step function response for the specified proportional gain. During the lab the students were to use the provided MATLAB/Simulink file (Fig. 4) to record the motor position data as a function of time with a specific step input value. The identified transfer function from Lab 1 was put in the *motor T.F.* block of Fig. 4 to simulate the motor position with the same step input. Students then quantitatively compared the theoretical response, the simulated data from MATLAB/Simulink, and the experimental data together in the postlab report. Through this lab activity, student should be able to relate the concept of feedback, damping ratio, natural frequency, and the dynamic performance parameters, such as overshoot, rising time, and settling time, to a real system.

Lab 3: PD Control Design

The objective of Lab 3 is to tune the step response of second order system using feedback controller. In this lab, students were asked to design a proportional and derivative (PD) feedback controller using root locus. This controller was used to control the motor angular position to track a reference input as shown in Fig. 3, with a new algorithm for G_c.

$$G_c(s) = K_p + K_D s \tag{5}$$

With a PD controller the system is second order, with an added zero in the transfer function.

$$\frac{\theta(s)}{R(s)} = \frac{a(K_P + K_D s)}{\tau s^2 + (1 + aK_D)s + aK_P} \tag{6}$$

For the prelab report students had to identify values of K_p and K_D that would result in the desired performance constraints including settling time and overshoot percentage. Students were encouraged to use root locus plots to assist in the design of their controller. There were multiple correct solutions, and students were provided with a simulation file to test and verify their values.

During the lab, each group had to update the control parameter values of $G_c(s)$ in the template MATLAB/Simulink file, and run the motors using their designed controller in order to meet the desired performance constraints. If their K_p and K_D values were unable to achieve the desired performance, students would need to update their values until they recorded data with the correct results. Their analysis had to display the controlled response and the values that their controller used. Through this lab activity, students were expected to observe how abstract controller gain can affect dynamic performance parameters of a real system.

It is worth pointing out that the *Saturation dynamics* block in Fig. 4 was used to simulate the battery limitation of LEGO MINDSTORM NXT. However, *saturation* is an advanced topic not covered in the current system dynamic course, thus cannot be analyzed quantitatively, but observable qualitatively from MATLAB simulation. In Labs 2 and 3, students used the theoretical tools to analyze/design the system, and afterwards included the saturation block in the simulation tools to check and tune the response, and eventually verify the system response in the experiment.

Early Technical Difficulties in the LEGO Labs

From Fall 2014 to Spring 2016, each semester, there were cases when the host computer froze as the MATLAB/Simulink algorithm was running on the LEGO MINDSTORMS NXT. When the host computer froze, no activity could proceed and the computer had to be restarted before the lab could be rerun. The cause of random freezing problems was eventually identified. Investigations pointed to the interruption of communication between the Bluetooth adaptor and the host computer, and the problem was resolved as of Fall 2016.

Critical Knowledges/Skills in Each Lab

Each lab covered several critical concepts from the course. Lab 1 was designed to address three concepts: transfer function, time constant of first order system, and steady state value of step response. Lab 2 addressed six concepts: feedback, rising time, peak time, overshoot of underdamped 2nd order system, settling time of underdamped 2nd order system, and the steady state value of underdamped 2nd order system. Successful completion of Labs 1 and 2 requires four levels of cognitive learning [7]: remembering, understanding, applying, and analyzing. Lab 3 addressed three critical concepts: root locus, PD controller, and the controller design. Successful completion of Lab 3 requires students to be engaged in designing/creating, a much higher level of learning than Labs 1 and 2 [7]. It is noted that although Lab 3 was more advanced, the curriculum does not expect students to complete a design project at the junior level. Labs 1 and 2 are better representations of curriculum expectations.

Individual Lab Surveys

For each lab, we asked students their confidence in understanding the technical concepts and methods immediately before and after the lab. In addition, we asked students to rate the helpfulness of each lab and invite them to openly comment in the postlab survey. Survey responses from Spring 2015 to Fall 2016 showed that students were positive in spite of aforementioned technical difficulties [3, 6]. In Spring 2017, a new set of surveys was created with additional features: (1) the surveys were modified to avoid leaning questions as suggested by Frontier in Education (FIE) conference paper reviewers; (2) in Lab 2 and 3 surveys, the 1-5 scale confidence level was further defined to match Bloom's taxonomy [7] where 1 equals remembering, 2 equals understanding, 3 equals applying, and 4 equals analyzing. Since for most concepts we didn't expect students to reach the "creating" level of Bloom's taxonomy, we defined 5 as students feeling confident teaching their peers. An example of the scale is shown in Table 1.

All surveys were anonymous but the two responses from each student were paired between before and after the lab using a student self-generated ID (the last four digits of a childhood phone number combined with the last four digits of a present phone number).

Learning Assessments

In Spring 2017, a series of learning assessments were collected to directly assess student learning: prelab report (individual), postlab report (group), related quiz question (individual), and related exam questions (individual). The assessment of prelab/postlab is the average grade for the questions in the prelab/postlab report that were tied with intended critical knowledge/skills. The related quiz

Table 1. An example of the prompts given for each level of understanding.

Targeted Bloom's Taxonomy	Confidence prompts provided (Overshoot example)
1. Remember	"I am able to recite a definition or find it in my notes"
2. Understand	"I can point out an overshoot on a graph of a system output"
3. Apply	"I can calculate overshoot given a transfer function of a second order system"
4. Analyze	"I can describe how overshoot changes given changes in the transfer function"
5. Teach*	I can achieve all previous and answer questions on the topic from my peers.

*The fifth level of Bloom's Taxonomy has been replaced with the ability to teach the ideas provided.

and exam questions test students on typical technical concepts and method used in each lab, but in a completely different context. A quiz requiring the ability to analyze (Bloom's Level 3) or higher was given on the same day when the postlab report was due. In order to identify the weakness of student knowledge in a relatively efficient manner, the quiz was graded on a 1-3 scale. A score of "3" was given when the student was nearly 100% correct while "2" means the student had the correct idea. The score "1" indicates the student attended the class. Absent students get "0" and were not included in the study. Exam questions of the same level were typically given within a week after the quiz and were graded with partial credit. It is noted that the learning assessment results cannot be paired with before and after lab surveys, due to their anonymous nature.

End of Semester Surveys

At the end of the semester students were asked to rank the different learning methods, and to provide open-ended feedback on the course and the labs. Students were asked four open-ended questions: (1) "What did you like about the LEGO labs?" (2) "What did you dislike about the LEGO labs?" (3) "Which of the three labs did you find to be the most useful in your education?" (4) "Which of the three labs did you enjoy the most?" Students were asked to rank two statements on a scale from 1-5 where 1 represented strongly disagreed and 5 represented strongly agreed: "I found the labs in this course to be helpful to my learning" and "I found the labs in this course to be enjoyable". Students were then asked to rank the various learning tools (i.e. lecture, homework, quiz, inclass discussion, lab) from a scale of 1-5, with 5 being the most helpful. Finally, the students wrote down their predicated course grade and were asked to provide additional comments.

Senior Surveys

In Spring 2017, a group of students who took the System Dynamics a semester or a year earlier were given a short survey. This group of students used some system dynamics related skills in their present courses or their ongoing senior design projects. Most of those students ran into early technical difficulties in the LEGO labs. The survey was intended to see if the LEGO labs had any long term effects in their learning and application of related system dynamics skills.

RESULTS

Most of the results presented in this section are from Spring 2017, with a total enrollment of 90 students. Survey results prior to Spring 2017, including those when students had technical difficulties, are discussed briefly in the section of Early Results.

Early Survey Results and Senior Survey Results.

Since the first offering of LEGO labs in Fall 2014, student perception of the labs had been collected through surveys every year, and the student feedback has always been positive [6]. The Wilcoxon signed rank test of Spring 2016 student survey results show that the confidence level of understanding technical concepts and methods significantly increased after the labs [6]. Senior survey results in Spring 2017 show that despite of the technical difficulties encountered by more than 80% of the students, half of the students reported LEGO labs were helpful to their learning and application of related system dynamics skills.

2017 Spring Before/After Lab Survey Results

In the Spring semester of 2017, students were asked to rate how confident they were in understanding each specific concept before and after each lab (Fig. 5 to 7). The results show that students consistently gained confidence in the reported understanding after each lab.

A Wilcoxon signed rank test of the paired data showed that confidence gain was significant for the majority of the concepts. After each lab the students also ranked the helpfulness of the labs in terms of their education. Table 2 shows the significance of the confidence gain and the average scores of the helpfulness of the labs. Each concept in Table 2 is aligned to the critical knowledge points of the lab, except in Lab 2 where Overshoot involves three critical knowledge points (peak time & overshoot, the steady state value was omitted due to its simplicity).

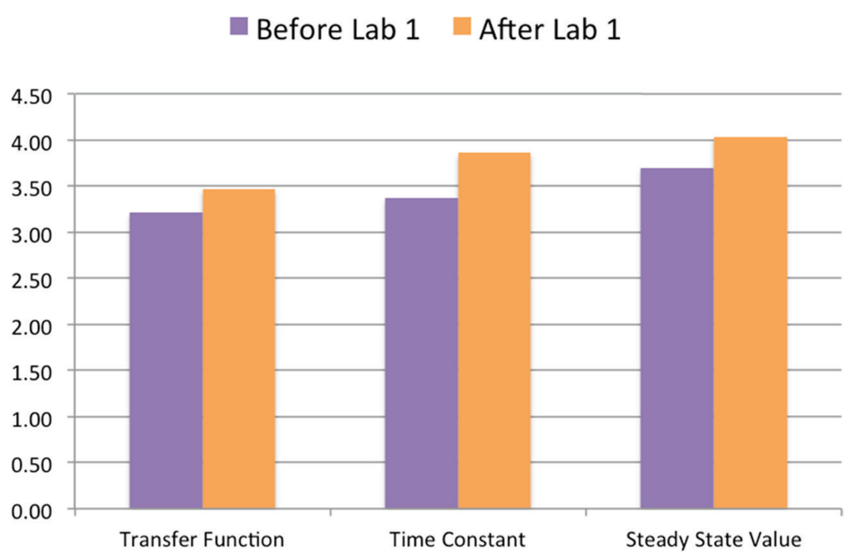

Figure 5. Confidence in understanding concepts before and after Lab 1.

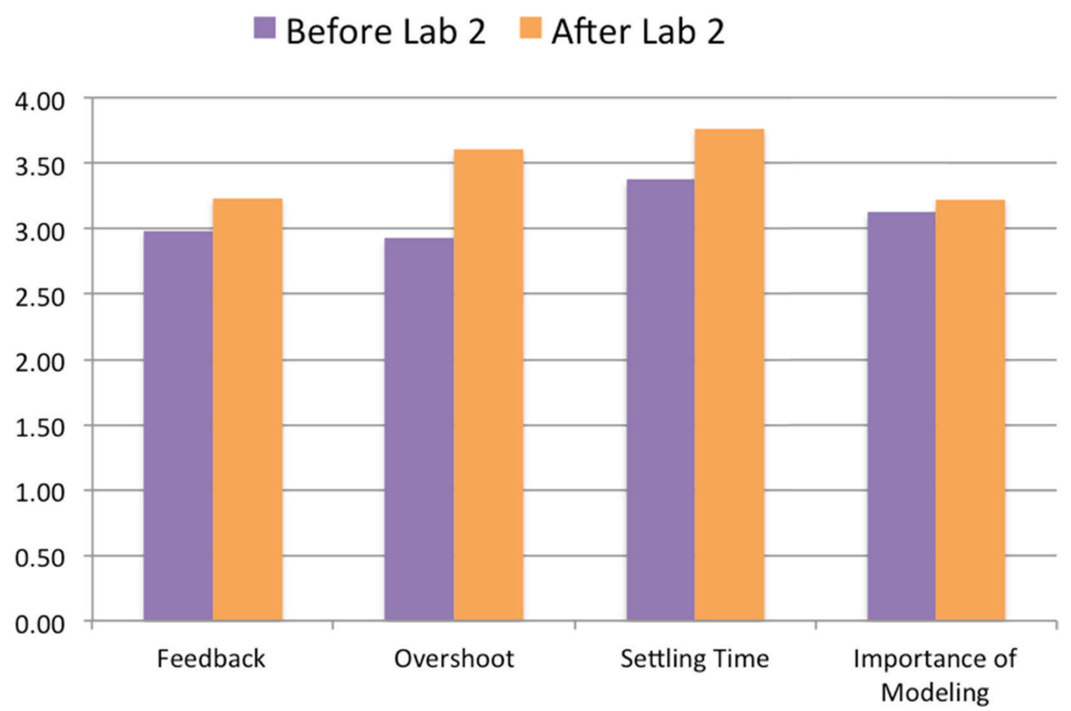

Figure 6. Confidence in understanding concepts before and after Lab 2. The scores for these labs correspond to the ranking shown in Table 1.

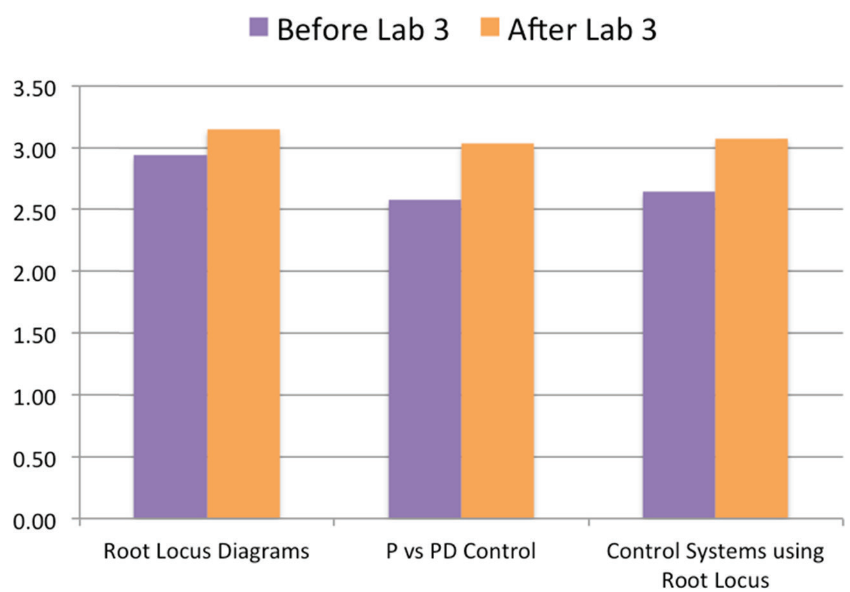

Figure 7. Confidence in understanding concepts before and after Lab 3. The scores for these labs correspond to the ranking shown in Table 1.

Table 2. Significance of Confidence Gain.

Concept	Prelab Score (mean)	Postlab Score (mean)	Helpful Score (mean)	Wilcoxon comparison
Lab 1				
Transfer Function	3.22	3.47	3.19	Significant at $p<0.01$
Time Constant	3.37	3.86	3.55	Significant at $p<0.01$
Steady State Value	3.70	4.04	3.65	Significant at $p<0.01$
Lab 2				
Feedback	2.99	3.24	2.80	Significant at $p<0.05$
Overshoot	2.94	3.61	3.22	Significant at $p<0.01$
Settling Time	3.41	3.76	3.18	Significant at $p<0.01$
Modeling	3.13	3.23	2.99	Not significant
Lab 3				
Root Locus Diagrams	2.94	3.15	2.88	Not significant
P vs PD Control	2.58	3.03	2.59	Significant at $p<0.01$
Control System using Root Locus	2.65	3.07	2.79	Significant at $p<0.01$

Although on average, the class confidence increased for all concepts, the differences in scores were not significant for *modeling* second order systems (Lab 2) or *root locus diagrams* (Lab 3). It is interesting that among all the concepts in Lab 3, the highest rating on helpfulness for *root locus* did not translate into a significant increase in the confidence of understanding.

In each postlab survey, students were given the chance to free comment on the lab. However, few students took the advantage. Based on the limited feedback collected, students seemed to feel positive about Lab 1, but suggested longer time to be allocated for Lab 2 and 3. They also commented that the wording of the instructions could be clearer.

Learning Assessment Results

To identify the effectiveness of the labs, we measured student performance by examining the class averages of prelab reports, postlab reports, quizzes, and relevant exam questions given after the labs. Fig. 8 illustrates the average assessment results for each lab.

In comparing the before and after lab grades, Lab 1 helped students the most whereas Lab 3 helped the least. This may be because the postlab reports were group reports, which by nature were more likely to yield a higher grade than an individual prelab.

When student learning was tested in a different context, such as the problems in the quiz, performance was significantly lower than that in the before/after lab activities. This is particularly true in Lab 3, which required design skill to be successful. The grading scale of quiz (1, 2, or 3 points) also

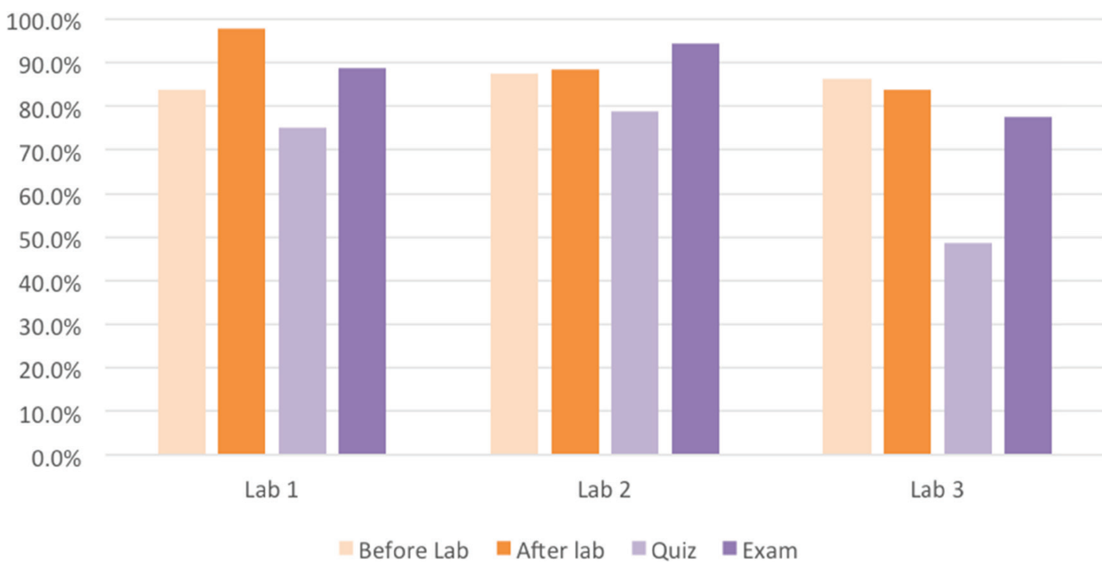

Figure 8. Average student score on the prelab, postlab report, quiz, and exam question associated with the learning objectives of the lab.

contributed partially to the lower grade in quiz. Typically, if a student knows how to do the majority of a problem they should get more than 66% credit on an exam. The low quiz grade after Lab 3 prompted the instructors to add another example in the following lecture as an additional resource for students to learn about the concepts. Eventually, student performance in the exams was above 75% even on the higher-level skills required for Lab 3.

End of Semester Survey Results

To analyze student feedback on what they liked and disliked about the LEGO labs in the end-of-semester survey, we generated a list of common keywords from the responses to represent the themes. The themes and the percentage of students represented are listed in Tables 3-4 below. Since many responses touched upon multiple keywords, and only the most common themes were presented, the percentages do not add up to 100%.

A common theme from the students was that they appreciated the hands-on experience to apply concepts they have learned, and then visualize the changes they have made. The novelty of using LEGO in class was seen as a pleasant break from regular lectures, and some students noted that they appreciated the experience to use MATLAB/Simulink. The complaints from students included the difficulties encountered in understanding the prelabs, which could be due to the lack of clarity in the directions given, and not having enough time to complete the tasks. Although some students

Table 3. Themes from student responses to "What did you like about the LEGO labs?"

Themes	Percent of Student Responses
Hands on	29.7%
Applying concepts	20.3%
Be able to visualize	20.3%
A break from lectures	17.2%
Matlab/Simulink experiences	10.9%

had a hard time understanding abstract concepts, others wanted more complex labs with parts beyond a claw. A small number of students disliked using MATLAB/Simulink.

The students were asked to rank their experience with the LEGO labs: if they found them useful and if they found them to be enjoyable. The majority (73%) of the students rated the labs to be somewhat helpful or higher, and a larger majority (84%) found the experience to be neutral or enjoyable. Student rankings of helpfulness and enjoyability are illustrated in Fig. 9.

When asked to identify the labs that the students saw most useful, the results were evenly spread across the 3 labs, with Lab 3 seen as slightly more useful, as seen in Fig. 10.

Students were asked to rank each instructional approach in the class from the least to the most helpful. The average score (Fig 11) indicated that students found the lectures and in-class discussions to be the most helpful, followed by homework, the labs, and finally the quizzes.

The students were also asked to predict their grades of the course, to see if the labs were more beneficial to students who may struggle with the theory. There was no significant difference in the responses of helpfulness of labs based on the students' perceived grades: students anticipating an A were as likely to enjoy the labs or find them useful as students anticipating a B or C.

Table 4. Themes from student responses to "What did you dislike about the LEGO labs?"

Themes	Percent of Student Responses
Have trouble understanding pre-labs	18.8%
Unclear directions	15.6%
Not enough time	14.1%
Difficulty with abstract concepts	9.4%
Wish the robot could do more	9.4%

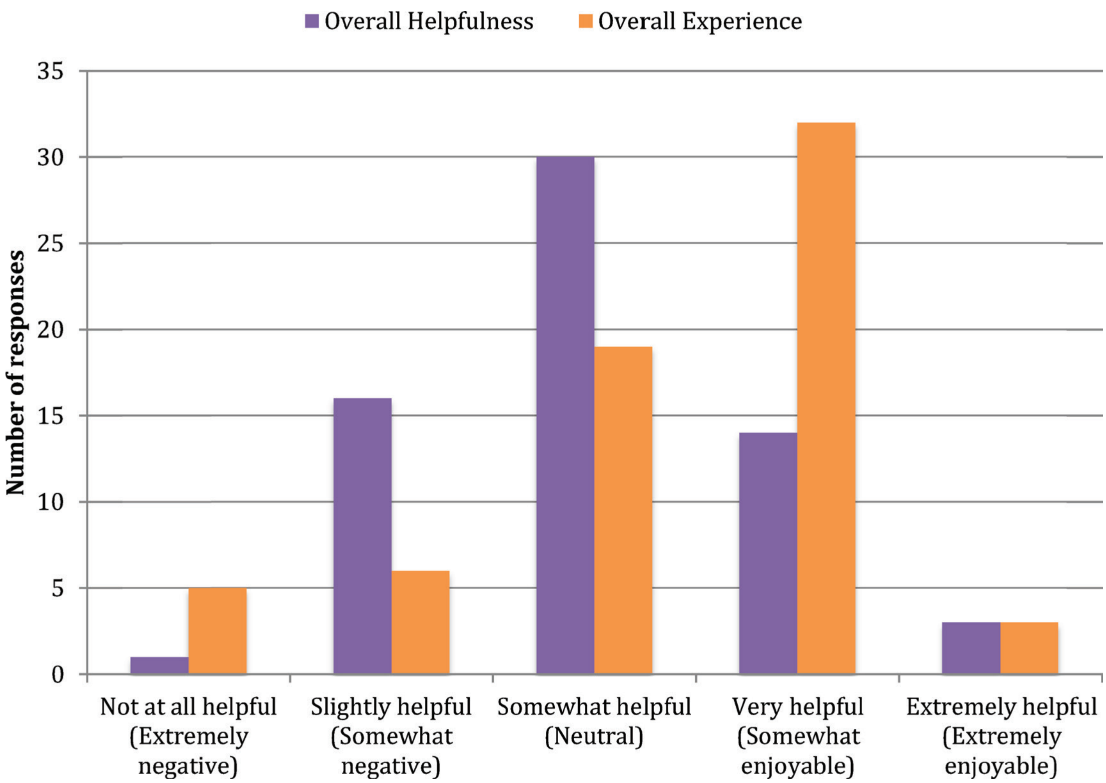

Figure 9. Student responses to the prompts "Rank the overall helpfulness (and overall experience) of the labs to your education."

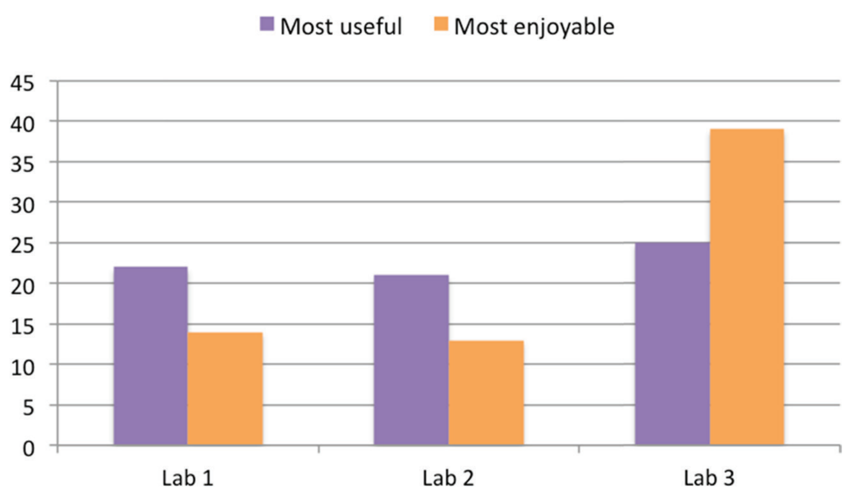

Figure 10. Student responses to the questions "Which of the labs did you find most useful to your learning?"

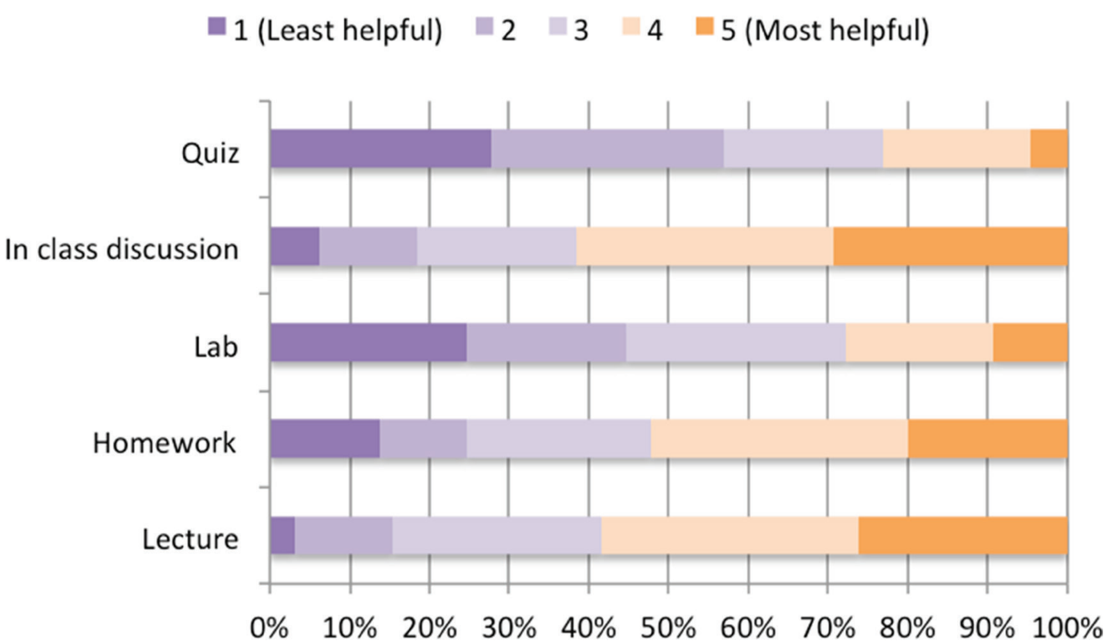

Figure 11. Student rankings of the learning techniques in class.

DISCUSSIONS

Perception of student confidence vs learning assessment results

For each lab, the student perception of confidence in their skills all increased from prelab to postlab. However, the increase in confidence does not always match the results from the learning assessments. As shown in Fig. 8, student performance was only higher in the postlab report than the prelab for Lab 1. It is understandable, however, that after each lab, student grades in the quiz were lower than the postlab report because problems in the quizzes required students to transfer their skills from the lab to a different context in order to solve the problem. Among all the labs, Lab 1 seemed to improve student skills the most in terms of postlab performance.

Comparison with the Lecture-example-exam Teaching Approach

State space modeling is another critical skill taught in System Dynamics. When benchmarked against Bloom's Taxonomy [7], it requires analyzing skills from students, a level lower than the design skills required for mastering root locus. State space modeling was taught in the traditional sequence of seven steps: lecture, example, practice, midterm exam, example, practice, final exam. Learning assessment over time shows a 7% increase in mastering from the midterm (56%) to the final exam (63%). In contrast, as shown in Fig. 5, the assessments on mastering root locus demonstrates a much higher increase – 29% in student performance from the after lab quiz (48%) to final exam (77%), likely attributed to having Lab 3.

Lessons Learned from Practice

Learning assessment results show that Lab 3 does not help students much in transferring skills from a familiar to an unfamiliar context. Individual before and after lab surveys revealed that many students (64%) enjoyed Lab 3 the most because it had a fully functioning robot. Students enjoyed the process of creating their own controller and watching the results. However, the learning assessment results failed to show Lab 3 helped them master the skills. A postlab quiz was able to identify the critical skills students missed and needed for remedial instructions. Almost 10% of students stated they had difficulty with abstract concepts also indicated student frustration, possibly related to the fact that the advanced feature of saturation effect in Labs 2 and 3 cannot be analyzed using the tools learned in the class. Because each lab needed two class periods to run, the instructor felt that Lab 3 could be revised to be a combination model where student do the design only followed by instructor running the lab. This new setup may take away some excitement from students, but it will secure more class time for explanation of saturation effect or for additional examples, as suggested by students in the open-ended comments.

Overall, there is strong evidence that LEGO labs help students in learning critical quantitative skills of System Dynamics. The unique setup of labs made it feasible to add hands-on experience with only three 75-minute labs in the current curriculum. These labs improved student performance at a degree similar to courses with more frequent and longer labs [14].

FUTURE PRACTICE

Based on the result of this study and student feedback, several practices will be revised for future classes. Lab 1 will be kept with little change. Lab 2 will be modified to add an additional case with no saturation effect to demonstrate the effect of *saturation* clearly. Lab 3 may be removed, but delivered in the model of students doing the design plus instructor running the lab. The time saved from Lab 3 (two 75-minute sessions) will be used for in-depth explanation of the *saturation* effect or adding more in-class examples.

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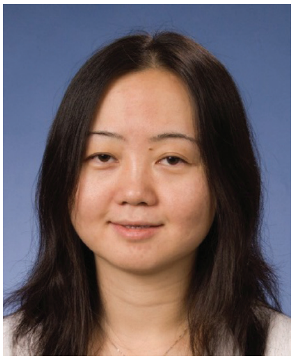

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