Enhance Hands on Experience of System and Control Using Low Cost LEGO Kits

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***Abstract*— System Dynamics is a required coursed offered to junior Mechanical Engineering students at Pennsylvania State University Erie, the Behrend College. It addresses the intercoupling dynamics of a wide range of dynamic systems: mechanical, electrical, fluid, hydraulic, electromechanical, biomedical, etc. It is a challenging course due to the abstract nature and increased 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 add hands-on experience for an undergraduate 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. Technical surveys before and after each lab have been analyzed and show that there is an improvement in students' confidence in topics from system dynamics with the labs. These three lab activities will evolve into two 2-hour labs of a one-credit lab course, Dynamics and Vibration, to be offered in Fall 2016. This lab course will complement the current courses in dynamics and vibration, attracting mechanical engineering students to pursue future careers in the field of dynamics and controls.**

Keywords—hand on experience, undergraduate education, Systems Dynamics

I. Introduction

System dynamics is an area of study in which the complex relationships among various aspects of a system are modeled and the behavior of the system over time is analyzed [1]. The most compelling challenges of teaching system dynamics is to teach students to think dynamically and holistically [2]. This course is offered as a one-semester junior course in the department of Mechanical Engineering in the school of Engineering of Pennsylvania State University Erie, the Behrend College. This course evolved from a previous course focused on the design of feedback controllers. Different from most other courses currently offered in Mechanical Engineering, this course involves the study of various subject areas, such as mechanical, hydraulic, pneumatic, thermal, electrical, electromechanical, biological systems, etc. It emphasizes a common approach using input output relationships. The interdisciplinary feature of this course and critical "system thinking" approach present a big hurdle to students. In addition, the complex mathematical tools make the course material too abstract to master [3]. The topics of this course include: system modeling using transfer function and state space model, stability, nonlinearity, time domain analysis, frequency domain analysis, root locus and Proportional Integral and Derivative (PID) controller design. Control theory is covered as an application of system dynamics. While hands on experience can be a useful tool in learning the material, the ready to use units in the market are costly. They are typically in the ranges of four thousand to more than ten thousand dollars per unit. Most low cost kits, such as arduino and raspberry pi, are not ready made and need to be programmed before use. This paper explores the applications of user-friendly LEGO MINDSTORMS kits to enhance hands on experience to the System Dynamics course. Before the introduction of LEGO MINDSTORMS kits, students' hands on experience was limited to only fifteen minutes of experiment with Quanser DC (direct current) controller unit (Quanser Inc, Canada) due to limited availability of these units [4].

In this paper, we first give the introduction of course structure and motivation of lab. The lab activities, together with surveys, are presented later, followed by the analysis of survey results and suggestion for future practice.

II. Method

A. *LEGO MINDSTORM NXT*

LEGO MINDSTORMS NXT education version is a programmable robotics kit including about 400 LEGO pieces, three servomotors, 4 sensors (ultrasonic, sound, touch, and light), 7 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 is sold for less than 400 US dollars [5]. In addition to its low cost and versatility, LEGO MINDSTORMS NXT is also compatible with MATLAB, the popular and powerful software already introduced in System Dynamics course. MATLAB/Simulink is introduced to students early in the course and students are required to use it in some homework assignments. In the lecture, the abstract mathematics-based method is always complemented by a visible simulation in Simulink. MATLAB has released the third party Simulink supporter package for LEGO MINDSTORM NXT hardware, which enables the user to create and run Simulink models on LEGO MINDSTORM NXT hardware. The support package includes a library of Simulink blocks for configuring and accessing LEGO MINDSTORMS NXT sensors, servomotors, and USB and bluetooth interfaces. It also enables the user to interactively monitor and tune algorithms developed in Simulink as they run on LEGO MINDSTORMS NXT. The low cost plus MATLAB/Simulink compatibility makes LEGO MINDSTORM NXT a very attractive method of offering hands on experience to students.

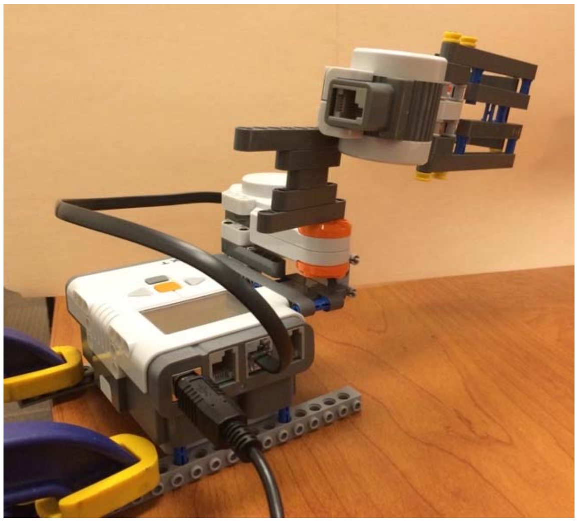

Fig. 1: A NXT brick with robotic claw acting as a load on the motor.

B. LEGO LABS

Since Fall 2014, three Lego labs were introduced in System Dynamics course in both spring and fall semesters, using twelve education version kits of LEGO MINDSTORMS NXT funded by the 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 and verification, (2) time response of a second order system, and (3) PD controller design. Two different instructors alternate in three semesters teaching System Dynamics course in Monday, Wednesday, Friday schedule with 50 mins regular lecture time. Those LEGO labs were offered using three 50 mins sections of regular lecture time. A common complaint about the labs was there was not enough time to complete the tasks. In Spring 2016, the regular lecture time was changed to Tuesday and Thursday weekly, with 75 mins each. Two instructors co-taught three lecture sections and offered those labs during three 75 min regular lecture time. Three lecture sections have 30, 18, 13 students respectively. The setup of each lecture section is identical. Each lab sections were limited to 18 students to allow adequate help from instructor except for Lab 1, which had one section with 30 students.

1) Lab Hardware setting

The hardware involved in those 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 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 NXT brick.

The NXT brick can run up servomotors using the 9V battery power. Each servomotor has a sensor (encoder) that can measure angular position with the resolution of 1 degree. The angular position of the servomotor recorded by the motor's encoder is transmitted from the LEGO brick through Bluetooth to MATLAB/Simulink. For these labs the data were recorded at 100 Hz instead of higher possible rate because of the limitation of encoder resolution. The percent of voltage provided to the motor could be determined through Simulink.

2) Lab activities

For each lab, students worked in self-selected groups of 2-3 individuals. For Labs 2 and 3 they needed to finish a short prelab regarding the technical analysis of a system prior to class. During each lab, students were given a MATLAB/Simulink template file for the experiment. Each group had a LEGO MINDSTROMS NXT kit to run their experiments. They had to set up the experiment, and adjust some parameters of the template file to run the experiment. After the algorithms were executed, students saved and analyzed the collected data using MATLAB. The analysis component of the lab could either be done during or after class, and each group needed to only turn in one form of analysis. The details of each lab are discussed in this section.

Lab 1: First Order System Analysis

In the first lab students use 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 servomotor that causes a robotic claw to rotate. 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.

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

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

$$G(s) = \frac{\omega_m(s)}{V_a(s)} = \frac{\frac{1}{K_e}}{\frac{J_m R_a}{K_t K_e} s + 1} \quad (2)$$

By adding the robotic claw in the second configuration, the mass moment of inertia would increase, resulting in a greater value for τ. For both configurations the process was similar. Each group had a NXT brick that they had to assemble with the motor attached. After connecting the NXT brick to the computer through both USB and Bluetooth, they could use the provided MATLAB/Simulink file (Fig 2) to apply voltage as a step function to the motor, and record the angular velocity as a function of time. Using MATLAB to plot the actual trajectory of the motor angular velocity, students could predict the time constant τ, as well as the transfer function of the first order system. For the analysis each group was asked to find the transfer function for loaded and unloaded systems, and plot a simulated first order response over the lab data for each configuration.

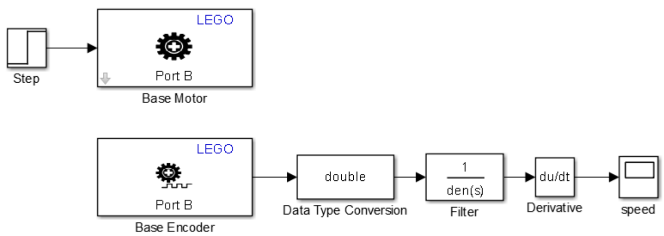

Fig. 2: The MATLAB/Simulink file of Lab 1.

Lab 2: Second Order System Analysis

For 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 90º. In Lab 2 the controller was a simple proportional controller.

$$G_c = K_p \qquad (3)$$

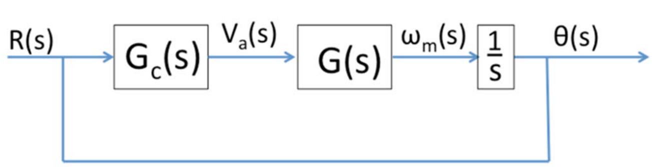

Fig. 3: The feedback loop representing the logic of Labs 2 and 3.

In the lab the controller K_p had two values: 5 and 10. This configuration resulted in an underdamped second order relation between the reference input and the angular position output.

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

For the prelab, the 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 two different proportional gain values. During the lab the students were to use the provided MATLAB/Simulink file (Fig 4) to record motor position data as a function of time for two scenarios, each one having a different proportional gain value. The identified transfer function from Lab 1 was put in *motor T.F.* block of Fig 4 to simulate the response. For the analysis of this lab the students were to compare their predicted response to the simulated data and the experimental data. With two different values of proportional gain, the resulting second order system demonstrates different damping ratio and natural frequency. Through this lab activity, student can relate the concept of feedback, damping ratio, natural frequency and the dynamic performance parameters, such as overshoot, rising time, settling time to a real system.

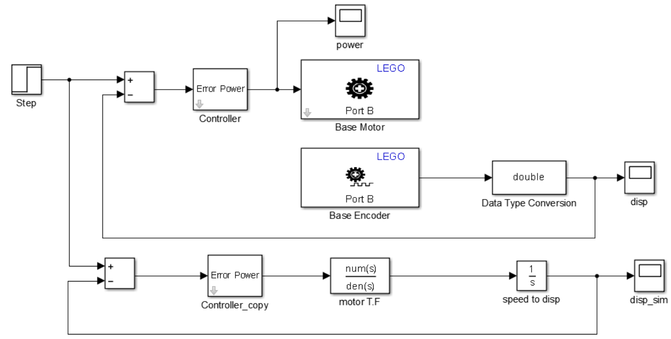

Fig. 4: The MATLAB/Simulink file of Labs 2 and 3.

Lab 3: PD Control Design

In the third lab, students were asked design a proportional and derivative (PD) feedback controller using root locus. This controller was to control the motor angular position to track a reference input as shown in Fig 3, with a new value for G_c.

$$G_c(s) = K_p + K_d s \qquad (5)$$

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

$$\frac{\theta(s)}{R(s)} = \frac{a(K_p + K_D s)}{\tau s^2 + (1 + aK_D)s + aK_p} \qquad (6)$$

For the prelab students had to identitify values of K_p and K_D that would result in the desired performace 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 their values.

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

C. *Surveys*

Spring 2016 is the first time we collected the same survey results in all lecture sections of system dynamics taught by different instructors. So spring 2016 survey results will be the focus of discussion in this section. For each lab, we ask students three to four questions on their perception regarding the technical concepts and methods learned in the System

Dynamics courses right before the lab. Right after the lab, the same questions were asked again. For example, in the Lab 1 surveys before and after the lab, we asked students to rate their confidence in the understanding of time constant on the scale of 1-5, with 5 being the most significant. All surveys are anonymous but kept pairwise between before and after lab discussion, homework, and lab in the importance of helping them understand concepts in the after-lab survey. In addition, students were asked to provide free comment in the after-lab survey.

D. Technical difficulties in the LEGO labs

Each semester, there were cases of the host computer freezing when the MATLAB/Simulink algorithm was running on the LEGO MINDSTORMS NXT. When the host computer freezes, no activity can proceed and the computer must be restarted before the lab can be rerun. Those random freezing problems were not specific to individual host computers or LEGO units, and would only occur in the running mode when the sensor data is collected in MATLAB through Bluetooth. To limit the occurrence of the host computer freezing, it was found that delivering the code to the hardware before running the simulation, but this did not completely prevent the technical difficulties. However these difficulties do not occur when running in a laptop with interior Bluetooth capability. It is suspected that it is the external Bluetooth adaptor that causes the most troublesome problem in running those labs, and the technical difficulties can be resolved by using a more reliable and compatible Bluetooth adaptor.

III. RESULTS

Survey results of all three sections were analyzed using Wilcoxon Signed Rank Test. Results shows that the mean value of students' rating on most questions in all three labs are higher in after-lab survey than that in before-lab survey, showing a positive perception of lab.

A. Concept ranking

Before and after each lab students were asked to rate the how much they agreed with a given statements listed in Tables 1-3 on a scale of 1 to 5, where 1 represented strongly disagreed and 5 represented strongly agreed.

Lab 1 was focused on studying the response of a first order system to a known input, and identifying the time constant and transfer function from the output. Table 1 shows the results of the surveys given before and after Lab 1. The confidence rose in the statements of understanding a transfer function ($P<0.01$) and time constant ($P<0.05$), and did not change for understanding steady state value. However, the average response for that statement was between "agree" and "strongly agree."

TABLE I. RESULTS OF LAB 1 SURVEY.

	Prelab mean value	Post lab mean value	Wilcoxon Signed Rank Test
"I feel confident in understanding the concept of *transfer function* with a physical system."	3.74	3.98	$p < 0.01$
"I feel confident in understanding the concept of *time constant*."	3.96	4.11	$p < 0.05$
"I feel confident in understanding the concept of *steady state value*."	4.21	4.21	$p > 0.05$ (not significant)

In Lab 2 the students were able to see how their system from Lab 1 responded in a feedback loop. Table 2 shows the responses to the surveys given before and after Lab 2. The increase in confidence in feedback and overshoot were very strong ($P<0.01$), while the increase in understanding settling time and modeling were still statistically significant ($P<0.05$).

Lab 3 required the most preparation, as students were instructed to design a control system for the LEGO claw. Table 3 displays the responses to the surveys handed out before and after Lab 3. This lab had the strongest change in concept confidence

TABLE II. RESULTS OF LAB 2 SURVEY.

	Prelab mean value	Post lab mean value	Wilcoxon Signed Rank Test
"I feel confident in understanding the concept of *feedback* with a physical system."	3.28	3.72	$p < 0.01$
"I feel confident in understanding the concept of *overshoot*."	3.78	4.17	$p < 0.01$
"I feel confident in understanding the concept of *settling time*."	3.87	4.12	$p < 0.05$
"I understand *the importance of modeling (i.e. transfer function)* in studying the step response of an underdamped 2nd order system."	3.55	3.92	$p < 0.05$

TABLE III. RESULTS OF LAB 3 SURVEY.

	Prelab mean value	Post lab mean value	Wilcoxon Signed Rank Test
"I feel confident in using *root locus* to design a controller."	2.41	3.23	$p < 0.01$
"I feel confident in understanding the *difference of proportional controller (P) vs proportional+derivative (PD) controller*."	2.30	3.11	$p < 0.01$
"I feel confident in understanding *how controller structure (P vs PD) and controller parameters (values of kp and kd) affects system performance (rising time, overshoot, etc)*."	2.26	2.96	$p < 0.01$

B. *Perception of Learning Effectiveness*

After each lab, students were asked to rank the various learning tools provided in the course from a scale of 1-4, with 4 being the most helpful. The results of these surveys are displayed in Figures 5-7. While Lab 1 had the least significant changes in concept knowledge, it was seen as more helpful at that point in the semester. By the end of the Lab 3, lecture was seen as the most useful learning method for the majority of the students, and the LEGO labs were seen as the least useful.

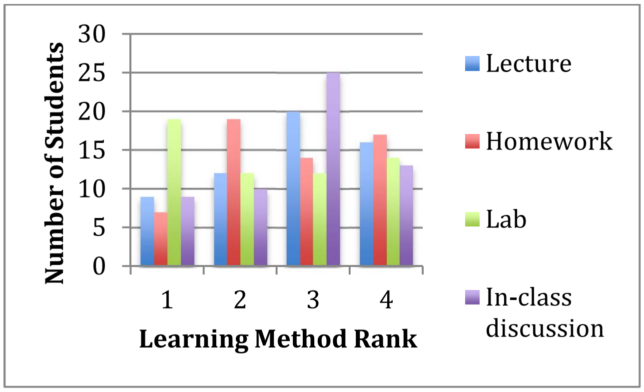

Fig. 5. Students' rankings of helpfulness of learning methods from 1-4 (4 being the most helpful) after Lab 1.

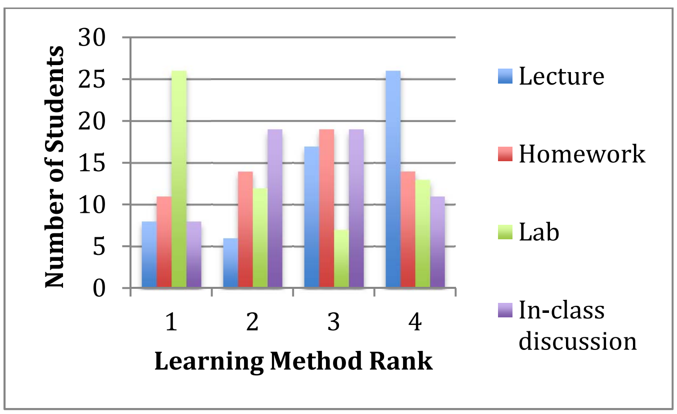

Fig. 6. Students' rankings of helpfulness of learning methods from 1-4 (4 being the most helpful) after Lab 2.

C. *Open Responses*

In the open-ended response section of the surveys, there was a range of responses. Some students found the hands on experience useful, but that the technical difficulties were a hindrance. The negative comments were focused on the technical difficulties, for example: "Bluetooth a hassle," "Lab didn't work for our group," and "These labs are frustrating."

Many comments showed the balance of the labs as a learning tool. "The lab was fun but one needs to know the material before doing the lab. So learning-wise, the lab wasn't very helpful but seeing a real meaning for the material was helpful." Another student stated "Homework helps me understand problem solving more, Lab helps me understand concepts more." In terms of the rankings a student stated that while the ranked the labs last, they still found them very useful.

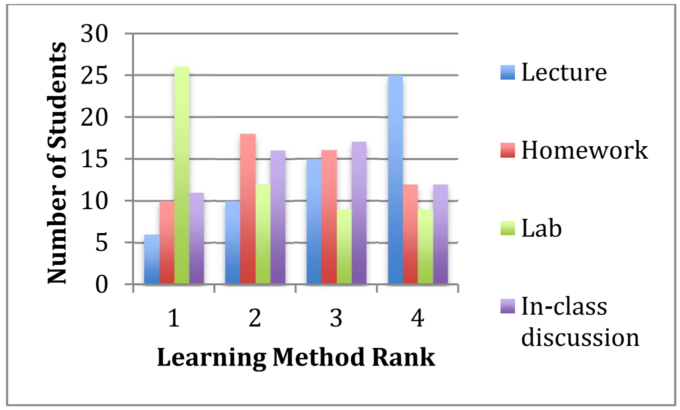

Fig. 7. Students' rankings of helpfulness of learning methods from 1-4 (4 being the most helpful) after Lab 3.

The positive comments focused on concept learning: "I liked the lab a lot! It was a great chance to see applications of the concepts" "The lab helps illustrate the significance and application of the models analyzed in class".

D. *End of Semester Survey*

At the end of the semester students were asked once more 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." Finally the students were asked to once more rank the different learning methods from 1-4.

For the open-ended questions there were several common answers. The most common responses to "What did you like about the LEGO labs" mentioned real world or hands on application of system dynamics (26 students), playing with LEGOs (15 students), having a change of pace from lecture (6 students) and using MATLAB (3 students). When asked "What did you dislike about the LEGO labs" the most common responses mentioned technical difficulties (45 students) and not having enough time for the labs (3 students).

A visualization of the students' responses to most useful and most enjoyable lab is shown in Fig 8. Lab 3 seemed to be ranked as the most useful for learning, and several students specified that the pre-lab was very useful. When ranking which lab the students found most fun, they would specify that their choice was influenced by technical difficulties.

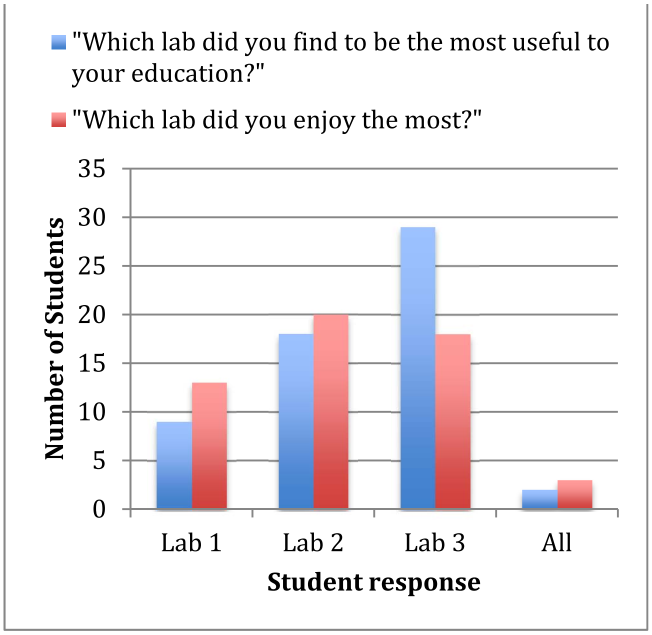

Fig. 8: Student responses when asked to choose a favorite lab in terms of learning and enjoyment

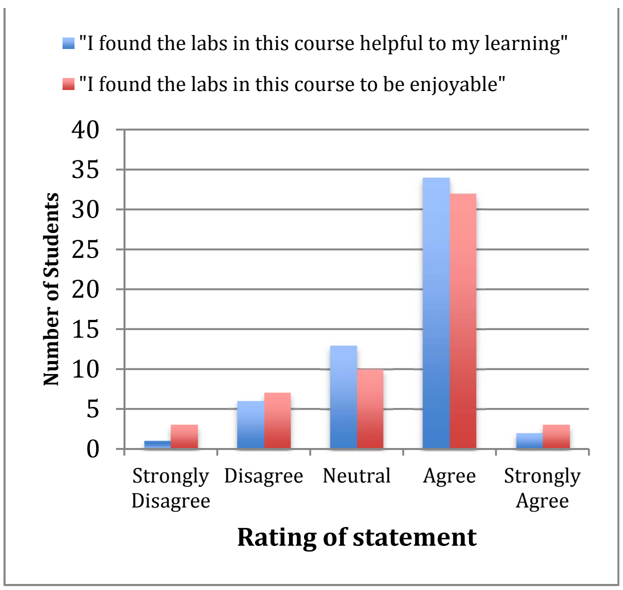

Fig. 9: Student ranking of statements at the end of the semester

The student ranking of statements shown in Fig 9 showed that many students did see the benefit in the labs. They were more likely to find the labs as helpful to their learning, but many students did find the labs enjoyable. To assess if there was a significant difference between the three sections of the course, the average ranking for these statements was compared across the different sections. The difference between sections was not found to be significant.

At the end of the course students were less polarized in ranking lecture as the most useful and lab as the least useful method of learning. The visualization of student rankings is shown in Fig 10.

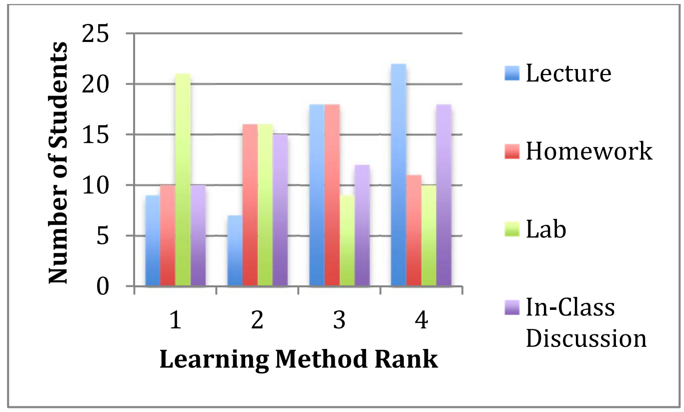

Fig. 10: Students' rankings of helpfulness of learning methods from 1-4 (4 being the most helpful) at the end of the semester.

In the open ended section at the end of the final survey, several students said that they think these labs are useful and important, and with the technical difficulties accounted for, they should be included in future semesters of this course.

FUTURE PRACTICE

Overall, there are strong evidences that Lego labs help students in learning System Dynamics. The instructors plan to continue offering those lab activities, and are working actively to resolve the technical difficulties. Bluetooth adaptor for the host computer has been identified as a major cause for technical difficulties in all lab activities. One instructor is working with the Penn State Behrend computer center and Mathworks Inc. to find a more reliable approach to sample motor encoder data.

A more comprehensive version of LEGO labs will also be included in an elective lab, i.e. Dynamic Systems and Vibration laboratory course, in Fall 2016. This lab course will complement the current courses in dynamics and vibration, attracting mechanical engineering students to pursue future careers in the field of dynamics and controls.

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