



## **Redesign of Lab Experiences for a Senior Level Course in Dynamic Systems with Controls**

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*At Kettering University, all mechanical engineering students take a two-course sequence in Dynamic Systems; the first course is Dynamic Systems with Vibrations, and the second is Dynamic Systems with Controls. In the past, the first course has been purely a lecture class, while the second has included both lecture and lab time. Previous student experiences, however, have indicated that the lab time was not effective at reinforcing the lecture portion of the course, so the courses were changed. A lab component was added to the first Dynamic Systems course, and the lab component of the second course was completely redesigned. This paper will focus on the changes to the lab component of the second course, Dynamic Systems with Controls.*

*The redesign of the lab experience was completed in two stages. In the first stage, a new set of lab exercises was designed, based on the use of the Mathworks<sup>®</sup> Matlab/Simulink software for simulation of dynamic systems and the design of their controls. Students who experienced this version of the lab experience were exclusively those who had not gone through the lab component of the first Dynamic Systems course. In the second stage, the use of Quanser<sup>®</sup> Qube-servo hardware with National Instruments<sup>®</sup> myRIO units was also integrated into the lab. The simulation labs were evaluated, with some simulation retained in the lab and some of the concepts shifted into hardware-based labs.*

*This paper will first present the background of the course and reasons for the redesign, including the desired student outcomes. Next, it will discuss the design of the simulation labs, followed by the design and implementation of the hardware-based labs. This discussion will include the key topics covered, the learning objectives of the labs, and the practical challenges in implementation. Finally, data will be presented on student evaluations of the lab experiences, and future changes based on this data will be discussed.*

### **Background**

Kettering University has for many years offered two primary courses in the area of Dynamic Systems and Controls. MECH330, Dynamic Systems with Vibrations, was taught as a four lecture hour course with no lab component. MECH430, Dynamic Systems with Controls, was taught as a four lecture hour course with two hours of laboratory. In truth, the two hours of lab were often used to provide additional hours of lecture material.

Ongoing course assessment indicated that neither course was fulfilling all of its planned learning outcomes. MECH330 had an outcome which required that students would learn how to model physical systems using Matlab/Simulink software, yet few students gained any measurable proficiency due to lack of laboratory time devoted to that activity. MECH430 had an outcome which required that students would learn how to control a physical device, yet without a laboratory experience that outcome was not possible.

Student evaluation of the courses indicated a lack of satisfaction with both courses. While MECH330 generally received very good evaluation scores, students recognized that they were not getting the experience with Matlab/Simulink that they expected. This omission often became

a problem in subsequent courses, where the students had no confidence in their Matlab/Simulink abilities. MECH430 typically received low evaluation scores and the students expressed concern that there was not a true laboratory component in the course.

The concerns identified by the students were often a reflection of their experiences during their co-operative education rotations. Every student at Kettering University rotates between an academic term and a co-operative education term, where students will work as engineering interns. The students do this rotation twice a year from the moment they enter the university. Because of this constant exposure to industry, students learn many of the ‘soft’ engineering skills that are difficult to teach in a classroom environment. However, this experience makes the students at Kettering ‘non-traditional’ students. They tend to filter their academic experiences through their work experiences. The students knew that Matlab/Simulink and a practical understanding of controls were essential skills that they often observed used at work.

The industry partners who sponsor the undergraduate students were equally vocal in expressing their frustration with the quality of the controls education that the students were receiving. This frustration did not just apply to Kettering students, but to most all university students. Industry representatives that met with faculty regularly pointed that classical closed-loop feedback theory was not something that was particularly useful to them. They needed students who could work with PID controllers and simple state machines. This feedback matches with the results of numerous studies, including the Controls Curriculum Survey conducted by the IEEE Control Systems Society in 2009, which quoted industry practitioners making statements such as “Controls curricula focus too much on math and not enough on physical intuition”, and “Control engineers need to be more holistic. Need to understand the physics of the application in at least some domains, be able to develop first principles based models and also be able to connect on the implementation level (real time, embedded implementation). The current curriculum emphasized the mathematical theory at the expense of the practical realization aspects.”<sup>1</sup>

As a result of the feedback from students and industry partners, both MECH330 and MECH430 were revamped. Both courses were switched to be three lecture hours and two lab hours. MECH330 added significant computer laboratory experiences to strengthen students’ Matlab/Simulink skills. Physical plants and controllers, the Quanser<sup>®</sup> Qube with National Instruments<sup>®</sup> myRIO, were purchased to allow students opportunities to have hands-on experiences with controlling physical equipment. The efforts are still ‘works in progress.’

In this paper, the redesign of the MECH430 lab is described. This redesign took place in two stages; in the first stage, the lab experiences were exclusively based on Matlab/Simulink, both due to difficulties in getting the laboratory equipment ready for the course and due to the fact that these students had not been exposed to the new lab component of MECH330. In the second stage, the lab equipment was integrated into the course. Each lab experience is described, along with the challenges faced in integrating the new lab equipment. Evaluation of the lab experiences is described, and the paper concludes with a discussion of the future development of the lab course.

### **Initial Redesign of Lab: Simulation-Based Labs**

While laboratory equipment had been purchased prior to the Summer 2014 academic term, there were some challenges in implementing it in the course. These challenges are described more

fully in a later section of this paper. Therefore, in the first stage of the lab redesign, all of the laboratory exercises were simulation-based, using the Mathworks<sup>®</sup> software, Matlab and Simulink. The full list of laboratory exercises is given in Table 1, with descriptions following.

**Table 1: Simulation-Based Lab Exercises**

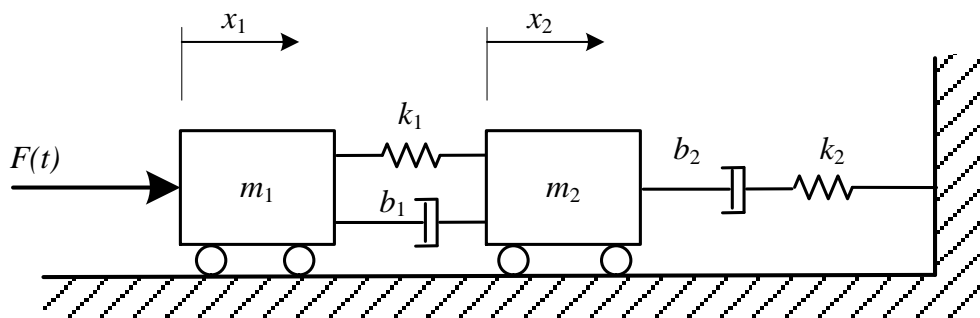
| Lab Number | Description                                     |
|------------|---|
| 1          | Introduction to Matlab, Simulink, and LabVIEW   |
| 2          | System Modeling in Matlab/Simulink              |
| 3          | Modeling and Simulation of Second Order Systems |
| 4          | Modeling and Simulation of Higher Order Systems |
| 5          | Introduction to Frequency Response              |
| 6          | Selection and Performance of Filters            |
| 7          | Introduction to Feedback Control                |
| 8          | Ziegler-Nichols PID Tuning                      |

*Lab 1*

Lab exercise 1 was an introduction to the Matlab/Simulink environment and to LabVIEW. While LabVIEW was not used at all in any of the subsequent labs, at the start of the term there was still a possibility that the equipment might be able to be integrated into the later part of the term's labs, and so students were introduced to it in the initial lab. In the Matlab/Simulink portion of this lab, students modeled a simple first-order system in Simulink, then created an initialization script file in Matlab so that they could easily change system parameters, then ran that system for several sets of values.

*Lab 2*

In lab 2, students derived equations for the dynamic system shown in Figure 1, using the bond graph approach, constructed a Simulink model of the system, and wrote a Matlab initialization script. When running the model, they sent data to the Matlab workspace and used Matlab's plotting commands to generate plots of the system outputs.



**Figure 1: Dynamic System Modeled in Simulation Lab 2**

### *Lab 3*

In lab 3, students created a Simulink model of a DC motor, assuming that the motor is a second-order system, and ran the model for different sets of values for the system parameters. They evaluated whether the system was overdamped, underdamped, or critically damped. In this exercise, they also computed the transfer function of the system and compared the results of running the original Simulink model to the results of simply inserting a transfer function block between the input and output.

### *Lab 4*

In Lab 4, students used the models they had created in Lab 2 and Lab 3 to find second-order metrics, and to study how knowledge of second-order systems could give them insight into the fourth-order system from Lab 3.

### *Lab 5*

Lab 5 introduced students to the concept of frequency response. In this exercise, students ran an instructor-provided Matlab script which produced graphs comparing input and input sinusoids of various frequencies for both first and second order systems, and then compared the gain and phase found from those graphs to a Bode plot.

### *Lab 6*

Lab 6 focused on the utility of Bode plots. Students were given a signal with multiple frequencies and transfer functions for several filters. They were then given several tasks, such as attenuating higher frequencies and retaining low frequencies, and instructed to choose the most appropriate filter for each task. After completing this portion of the lab, students were presented with several Bode plots and asked to estimate the transfer functions of those systems.

### *Lab 7*

In Lab 7, students simulated a first-order plant in a feedback control system with proportional control. The simulation was performed both with and without sensor noise, and with and without a disturbance present.

### *Lab 8*

Lab 8 introduced students to the use of the Ziegler-Nichols Ultimate Cycle Method for tuning a PID controller. Students were given a plant transfer function, and they built a simple Simulink model of this plant with a PID controller. They then followed the standard Ziegler-Nichols tuning method to set the gains, simulated the system, and evaluated the marginal stability condition from a root locus plot of the system.

## **Second Stage of Lab Redesign: Integration of Hardware**

In the second stage of the lab redesign, the Quanser<sup>®</sup> Qube was introduced, with the Qube driven by National Instruments<sup>®</sup> LabVIEW software. Initially, it was hoped that the Qube could be integrated into the lab during the Summer 2014 term; however, there were some significant

challenges in setting up the Qube so that it could be used. The primary difficulties were in the software installation process. The graduate student setting up the equipment found that there was no clear guidance on how to navigate the various versions of LabVIEW that might be installed in the lab, the versions of the Quanser<sup>®</sup> RCP toolkit that were required, and the LabVIEW add-ons for the myRIO controller. Several different set-up guides were required, as well as a certain amount of trial and error. Furthermore, when initially plugging in the myRIO to do a lab, at times the computer would ask the user if he/she would like to perform one of a series of operations, including the choice of configuring the myRIO.

If the user selected the option to configure the myRIO, it would cause problems; a formerly working unit would no longer work with the Qube after it was “set up,” requiring the graduate student to re-configure the unit and putting it temporarily out of service. Both students performing the lab, and lab instructors who would be subsequently teaching the course, had to be educated on the problems caused by choosing that option.

Once the units were put into service in the lab, it was found that the ribbon cable connector between the myRIO and the Qube was hard to remove; due to the risk of damaging the cable from frequent removal and re-insertion, it was decided to store the units with the ribbon cable left attached. This required the units to be handled carefully during transport, in order to avoid putting unnecessary stress on the ribbon cable.



**Figure 2: Quanser<sup>®</sup> Qube with Inertial Disk and myRIO Controller**

When the Qube was integrated into the lab, two simulation-based labs were retained, due to the limitations of the Qube. The full list of laboratory exercises is given in Table 2. Many of the labs were based on provided labs by Quanser<sup>2</sup>, but these labs were typically augmented by Simulink modeling or additional questions that the students needed to answer. All but one of the labs using the Qube utilized the inertial disk, shown in Figure 2; the remaining lab utilized the inverted pendulum.

**Table 2: Hardware-Based Lab Exercises**

| <b>Lab Number</b> | <b>Description</b>                   |
|-------------------|--------------------------------------|
| 1                 | Getting Started with the Qube        |
| 2                 | First Principles Modeling            |
| 3                 | Modeling of the Inverted Pendulum    |
| 4                 | Introduction to Frequency Response   |
| 5                 | Selection and Performance of Filters |
| 6                 | PD Control                           |
| 7                 | Ziegler-Nichols PID Tuning           |

*Lab 1*

The first lab experience was simply hooking up the Qube and running several existing VI's (Virtual Instruments) provided by Quanser<sup>®</sup>. The primary purpose of this lab was to ensure that students were able to hook up the hardware properly and download, unzip, and run VI's.

*Lab 2*

The second lab was based on the Quanser<sup>®</sup> lab, "First Principles Modeling", with some additional material and exercises added. In this lab, students were compared first and second order models of the Qube, with the inductance neglected in the first order model, for different values of electrical inductance, and were asked to evaluate Quanser's claim that the inductance could be neglected.

Students next set up the Qube, and ran a Quanser VI which input a series of pulses for the input voltage, and displayed both the actual angular position of the Qube and the position that was calculated based on the first-order system model. Students ran the model for different values of the key parameters – resistance, torque constant, and inertia – and were instructed to choose which set of parameters best matched the performance of the actual hardware.

*Lab 3*

The third lab was based on the Quanser<sup>®</sup> lab, "State Space Modeling", with the addition of some Matlab/Simulink work. In this lab, the students were given the linearized equations describing the inverted pendulum; they then had to put them in state-space form, and model them in Simulink. They ran that model, along with an instructor-provided model of the non-linear system, and compared the models to determine when the linearized model was reasonably accurate and when it was inaccurate.

After evaluating the simulation results, they then ran the State Space Modeling VI provided by Quanser<sup>®</sup> (utilizing a series of step inputs), and answered a set of questions about the behavior of the inverted pendulum.

#### *Lab 4*

The fourth lab was created by the lab instructor, and focused on frequency response. This was somewhat similar in concept to the fifth simulation lab of the previous term, but was performed with the Qube. The students ran a VI which sent a sinusoidal voltage signal into the Qube, and which displayed the position and velocity of the inertial disk as a result of this voltage signal. This position and velocity data was then used to find the magnitude and phase of the Qube's response for position and velocity, and then was compared to the magnitude and phase that were computed from the given dynamic equations for the Qube.

#### *Lab 5*

Lab 5 was a purely simulation-based lab, based on Lab 6 from the previous academic term. In this case, the second part (identification of Bode plots) was dropped, and an additional filtering task was added.

#### *Lab 6*

Lab 6 was based on the existing Quanser<sup>®</sup> lab, "PD Control". The VI provided by Quanser was modified by the instructor so that data could be sent saved to a flash drive, for further analysis and for producing good-quality graphs. Students were asked to first evaluate the root-locus plot of the Qube's transfer function for position, and comment on what kind of behavior they expected with a proportional controller. They then set the derivative gain to zero for the PD controller, and looked at the experimental and theoretical results of different proportional gains, particularly the maximum percent overshoot. They were then given a set of specifications for the controller's performance, and had to tune both the proportional and derivative gains in order to achieve those specifications.

#### *Lab 7*

The final lab experience was identical to Lab 8 from the previous academic term, in which students performed Ziegler-Nichols tuning, using the Ultimate Cycle Method, on a simulated system. This simulation lab was retained because the Qube did not lend itself to a Ziegler-Nichols tuning experiment. The inverted pendulum, in addition to being a complex non-linear system, was not stable; the inertial disk was not of sufficiently high order to perform Ziegler-Nichols tuning.

### **Evaluation of Lab**

Students in all classes, both lab and lecture, have the opportunity to complete an instructor-course evaluation at the end of every term. The evaluation is the IDEA survey, which is used by many universities throughout the country.<sup>3</sup> These results can be used, and often are, to determine how well the ABET objectives A-K are being met.<sup>4,5</sup> However, during the Summer 2014 term, very few students completed the evaluation for the lab class. The lab instructor therefore engaged students in individual conversations about the lab, in order to better evaluate which exercises



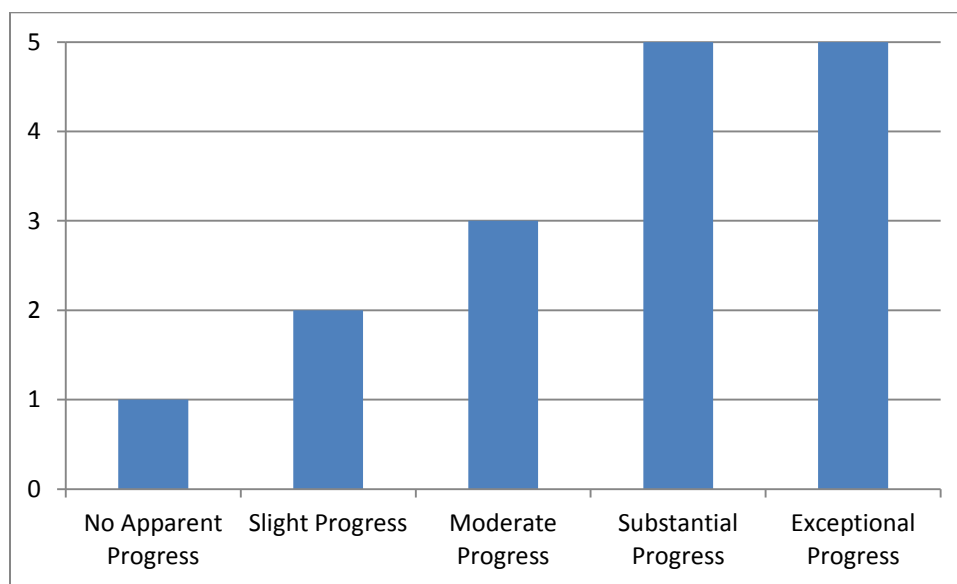
were worthwhile and which needed improvement, and this information was incorporated into the second stage of the lab redesign. As a part of this evaluation, two of the simulation-based exercises were retained, as described.

During the Fall 2014 term, students were very strongly encouraged to complete the instructor-course evaluation. Since this is an on-line evaluation, students were given time in the computer lab during class time to complete it. As a result, out of the 41 enrolled students in all sections, 28 of them (68%) completed the evaluation for the lecture portion of the class, and some of them included comments about the lab in that evaluation. Sixteen students (39%) completed the evaluation for the lab. Obviously, some students evaluated the lecture but did not complete the evaluation for the lab; however, it is not known whether all of those 16 students were among the 28 who evaluated the lecture, or whether there were some students who evaluated the lab but did not evaluate the lecture.

Results of the instructor-course evaluation were analyzed for those questions that are most relevant to a laboratory class in which students are attempting to learn practical applications of material and where they are working with a team. Students were asked to rate their progress on several objectives of the course on a five-point scale, where the scale ranged from 1 (No Apparent Progress) to 5 (Exceptional Progress). Averages were calculated, and in addition the distributions are shown. It can be noted that, in general, students had positive views of the lab, although there was one student who did not seem to feel that the lab was valuable to him or her.

#### *Gaining Factual Knowledge*

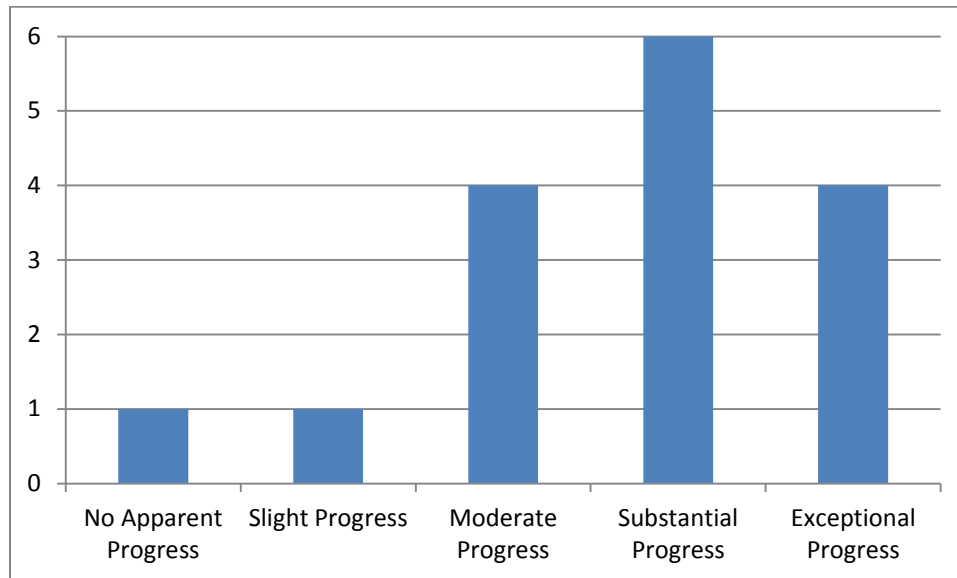
On the objective of gaining factual knowledge, students generally felt positively about the lab, with an average rating of 3.7. The distribution of students' ratings is shown in Figure 3.



**Figure 3: Student Evaluations for Gaining Factual Knowledge**

*Learning Fundamental Principles, Generalizations, or Theories*

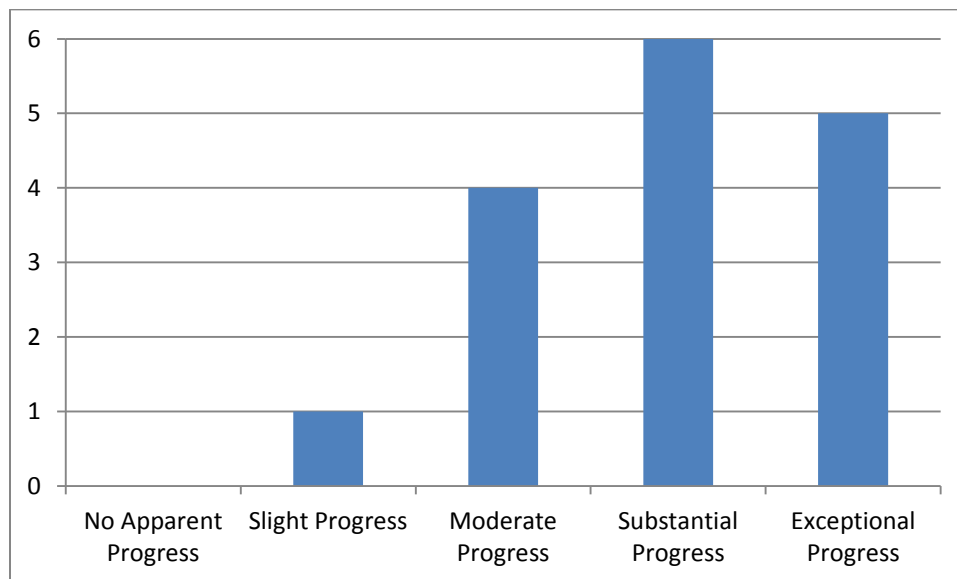
On this objective, students again had generally positive views, with an average rating of 3.7. The distribution of students' ratings for this item is shown in Figure 4.



**Figure 4: Student Evaluations for Learning Fundamental Principles, Generalizations, or Theories**

*Learning to Apply Course Material*

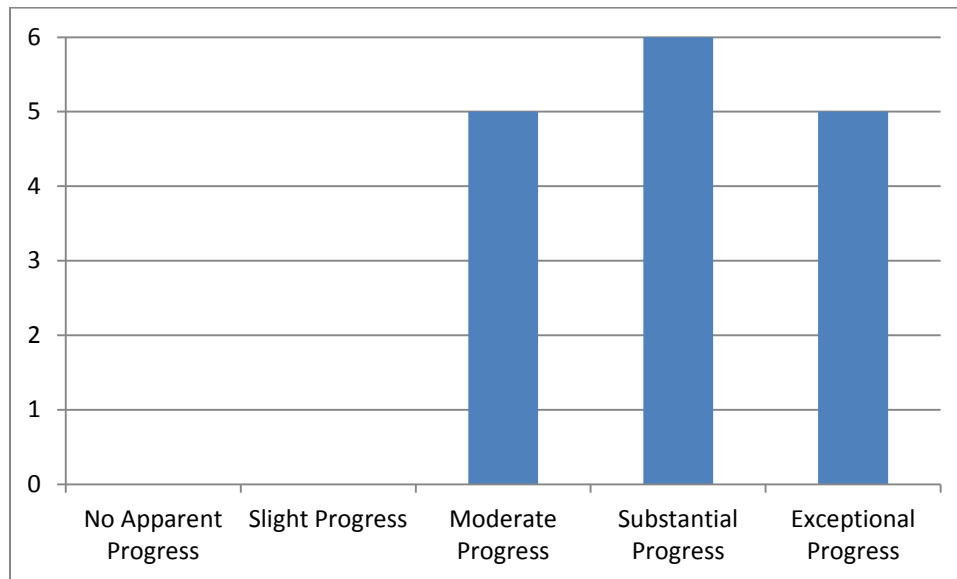
On this objective, students' views were even more positive, with an average rating of 3.9. The distribution of students' ratings for this item is shown in Figure 5.



**Figure 5: Student Evaluations for Learning to Apply Course Material**

*Developing Specific Skills, Competencies, and Points of View Needed by Professionals in the Field*

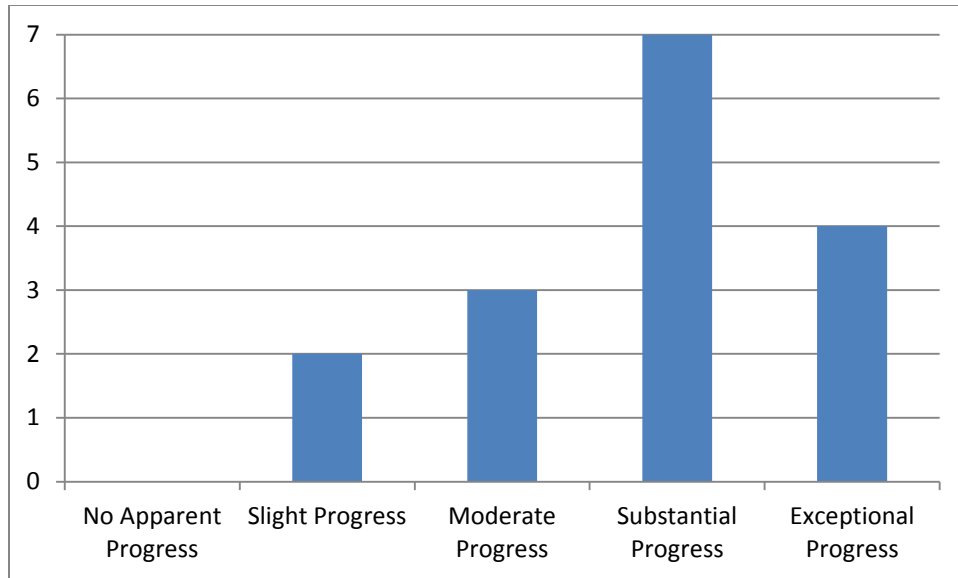
Students also rated their progress well on this objective, with an average rating of 4.0. The distribution of students' ratings for this item is shown in Figure 6. It can be noted that, not only is the average high, but all of the students who filled out the evaluation felt that they made at least moderate progress towards this objective.



**Figure 6: Student Evaluations for Developing Specific Skills, Competencies, and Points of View Needed by Professionals in the Field**

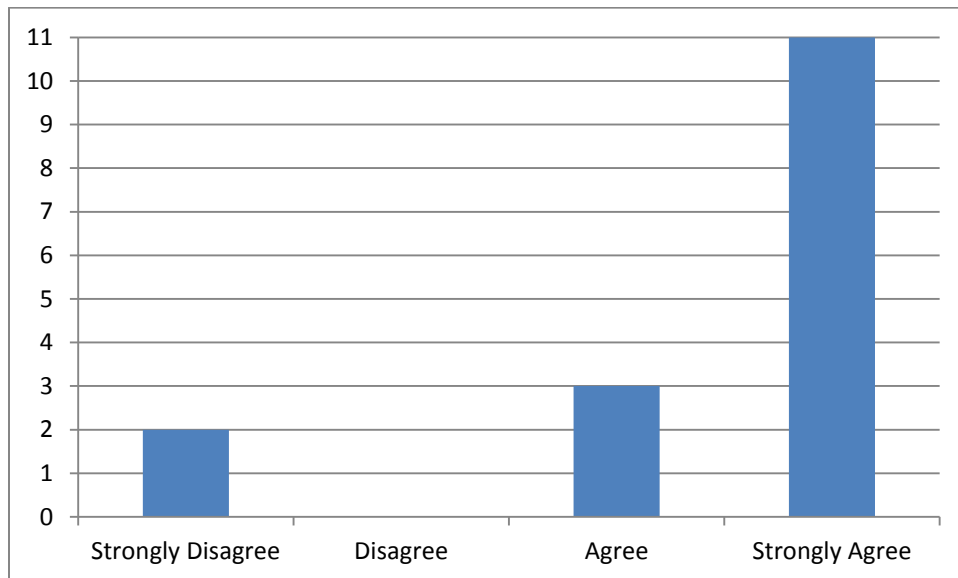
*Acquiring Skills in Working with Others as Members of a Team*

Since students needed to work with lab partners to accomplish the labs, it was also felt that this is an important objective of the course. Students had generally positive feelings about this, with an average rating of 3.8 for this skill. The distribution of students' evaluations is given in Figure 7. Again, it can be noted that even the student who felt that he or she made no apparent progress in some areas felt that he or she did make some progress in this area.



**Figure 7: Student Evaluations for Acquiring Skills in Working with Others as Members of a Team**

The final quantitative question from the IDEA course evaluation that was selected for analysis is the question of students' views of the lab equipment. As part of the evaluation for any lab class, students are asked to rate their level of agreement with the statement, "The lab equipment represented current technology." This item is rated on a four-point Likert scale, ranging from 1 (Strongly Disagree) to 4 (Strongly Agree). While a small number of students did not feel that the lab equipment represented current technology, the majority did, with an average rating of 3.4. The distribution of ratings is given in Figure 8.



**Figure 8: Student Ratings of Lab Equipment as Current Technology**

While most students' comments, if any, focused on the performance of the instructor, a few students did comment specifically on the lab material. Student comments on the labs were generally positive, with one student simply saying that "Lab was fun!" There were several students who, while they had positive views, recognized that the lab is a work in progress and still requires further improvement. One of the more extensive comments of this nature indicates this quite clearly:

I am rating the course as excellent even though a lot of wrinkles need to be ironed out. The course is headed in the right direction. The students I talked to three years ago could barely even describe what the course was about or where it was used. They have a GPA above 2.8. I feel I have a solid understanding of the course material and what the course is about. So I believe the course is headed in the right direction and will improve in the coming terms.

At the conclusion of the Fall 2014 term, students were also asked to complete a short survey, in addition to the standard instructor course evaluation that has been described. The survey contained seven questions. The first five items used a Likert scale, with choices of 1 (Strongly Agree), 2 (Agree), 3 (Neutral), 4 (Disagree), and 5 (Strongly Disagree). Those items were:

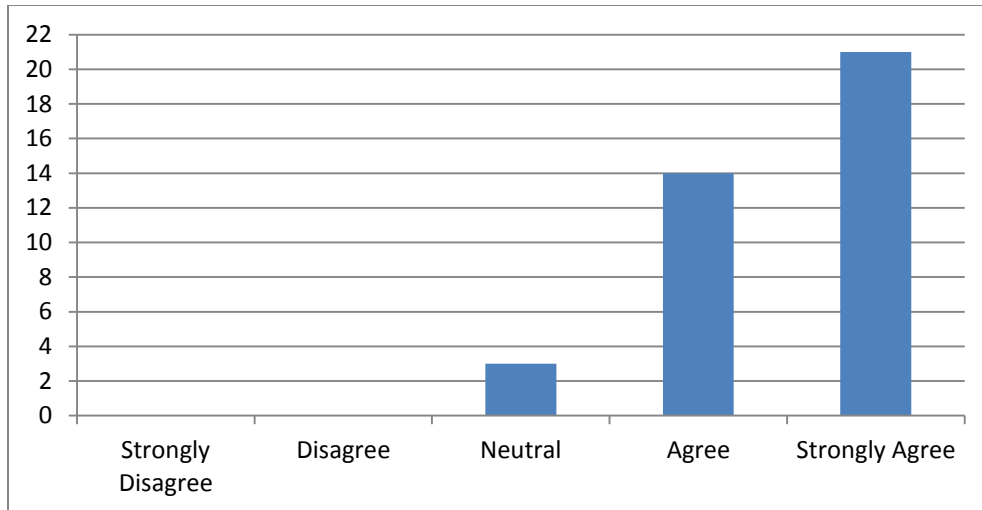
1. Overall, the simulation-based labs (filter selection and performance, Ziegler-Nichols PID tuning) reinforced the material you learned in the lecture.
2. Overall, the lab experiments with the Qube reinforced the material you learned in the lecture.
3. The labs helped you to understand the theoretical aspects of modeling and controls.
4. The labs helped you to understand the practical issues involved in modeling and controls.
5. The labs enhanced the course material.

The last two questions asked students to choose up to 3 lab experiences that they felt were the most valuable, and up to 3 lab experiences that they felt were the least valuable. All questions contained space for students to add additional comments, if desired. All students present on the last day of class completed this survey, providing a larger pool of data for the analysis of the lab. The total number of students who participated in this survey was 38, or 93% of the enrolled students.

1. *Overall, the simulation-based labs (filter selection and performance, Ziegler-Nichols PID tuning) reinforced the material you learned in the lecture.*

The students overwhelmingly agreed that the simulation-based labs reinforced the material in the lecture, with an average rating of 4.47. Only a small number of students felt neutral about this issue and no students disagreed with it. The distribution of ratings is given in Figure 9.

The student comments verify that the lab was clear and understandable. Also, some of the students indicated that filter selection was not fully understood until they completed the lab. As an area of improvement, a few students indicated that the lab was too easy and just "plugging in" numbers did not present much of a challenge.

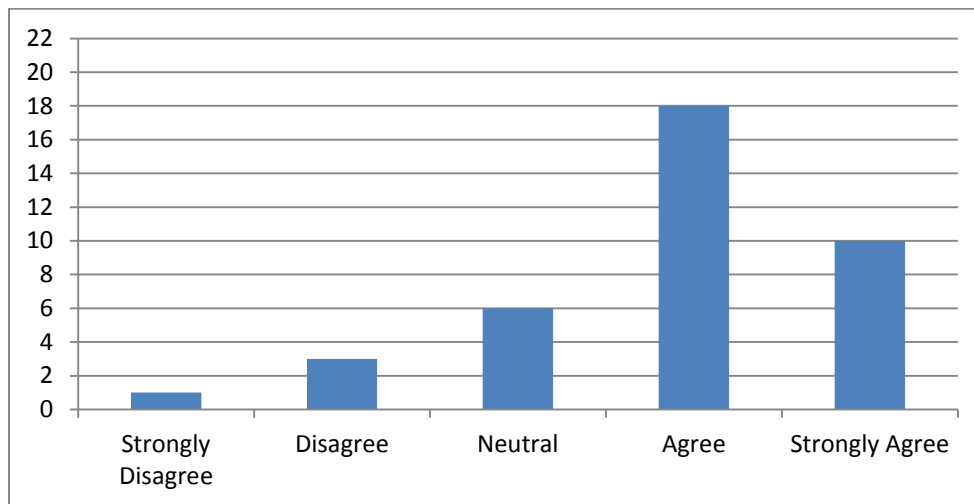


**Figure 9: Student Survey Results: Question 1**

2. *Overall, the lab experiments with the Qube reinforced the material you learned in the lecture.*

The students generally thought that the Qube reinforced the material that they learned in the lecture, with an average rating of 3.87. About 23.7% of the students felt neutral or disagreed about this issue. The distribution of ratings is given in Figure 10.

The student comments indicate that the Qube gave them a “real life sense” of the theory. An area of improvement is that more instruction may be required because the Qube is a little complex.

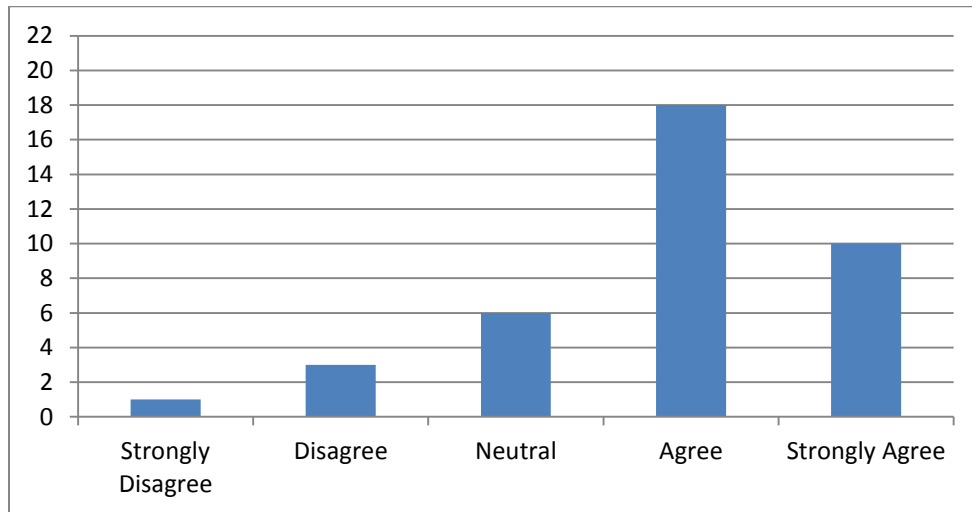


**Figure 2: Student Survey Results: Question 2**

3. *The labs helped you to understand the theoretical aspects of modeling and controls.*

The students generally felt that the labs helped them to understand the theoretical aspects of modeling and controls, with an average rating of 4.11. Only 21.1% of students felt neutral or disagreed about this issue. The distribution of ratings is given in Figure 11.

Virtually all of the student comments confirm that the labs helped the students connect theory with practice. No students offered areas of improvement here.

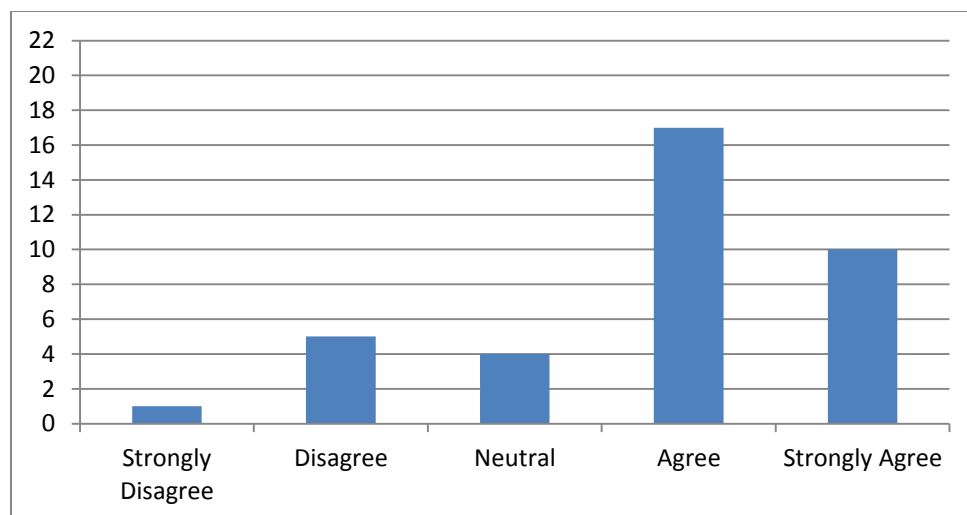


**Figure 11: Student Survey Results: Question 3**

4. *The labs helped you to understand the practical issues involved in modeling and controls.*

The students generally thought that the labs helped them to understand the practical issues involved modeling and controls, with an average rating of 3.82. About 26.3% of students felt neutral or disagreed about this issue. The distribution of ratings is given in Figure 12.

The student comments indicate that the labs helped with practical issues, especially regarding experimental limitations. As an area of improvement, some students thought that additional hardware (other than the Qube) would add value to the laboratory experience.



**Figure 12: Student Survey Results: Question 4**

5. *The labs enhanced the course material.*

The students significantly agreed that the labs enhanced the course material, with an average rating of 4.42. Only a small number of students felt neutral about this issue and no students disagreed with it. The distribution of ratings is given in Figure 14.

There were only five comments regarding how the labs enhanced the course material. All five comments are listed below.

Supporting comments are:

Overall having the lab made the class better. We also appreciated shorter lectures.

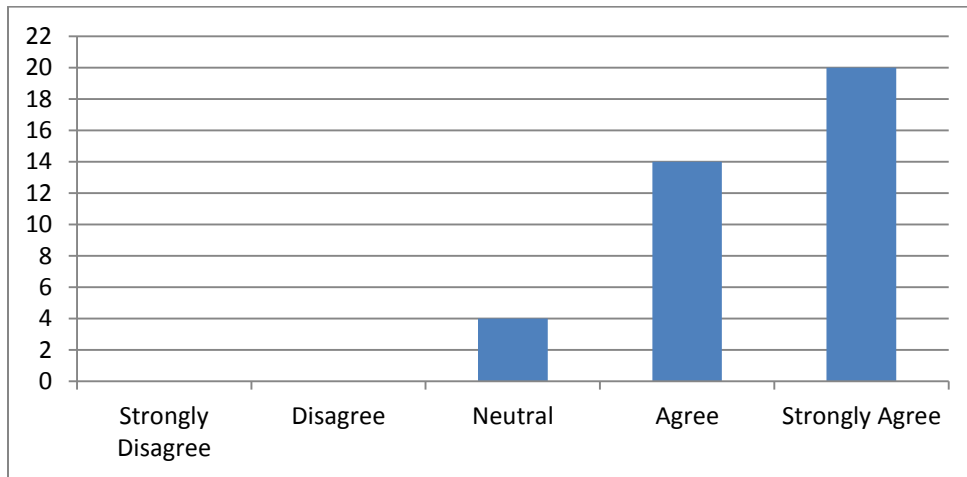
Yes, it was very valuable to learn a bit about Labview and Simulink/Matlab.

Areas for improvement are:

The labs seemed poorly balanced. Some took lots of time but others were very quick.

This was better towards the end of the term. I did not feel that for the beginning labs enhanced [sic].

I feel the lab did some, but seeing the controller we create to do something in reality would be better [sic].



**Figure 13: Student Survey Results: Question 5**

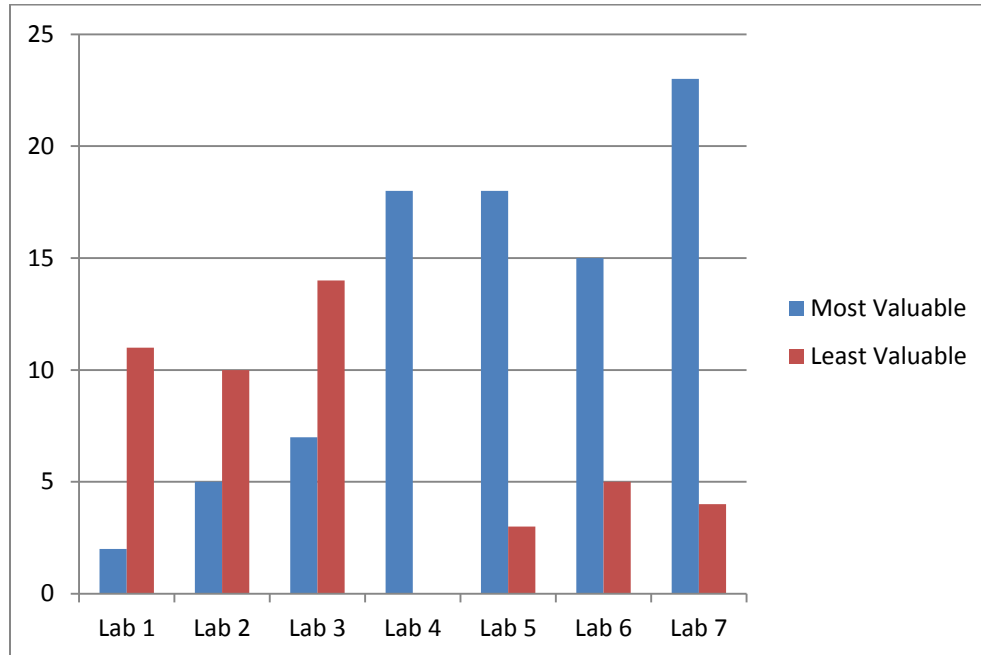
*Least valuable and most valuable labs*

The student rankings of least valuable and most valuable labs are shown in Figure 14. The later labs (labs 4-7) were clearly ranked more valuable than the earlier labs. According to student comments, the following observations can be made.

- 1) The first few labs had a steep learning curve.
- 2) The later labs had a strong correlation to the work done on the students' final project.
- 3) The later labs helped understand class theory better than the earlier labs did.



- 4) Lab 3, which was the least valuable lab, involved an inverted pendulum. Students did not like this lab because it did not work properly and it was too complex. Based on these comments, this lab may be eliminated in the future.



**Figure 14: Most Valuable and Least Valuable Labs**

### **Discussion and Conclusion**

Overall, the redesigned lab appears to be a positive experience for the students, which comes much closer to meeting the course objectives. While some students saw little value in the lab, as noted in the lab evaluation data, others felt that the lab was useful and represented a significant improvement over what they had heard about the course from their friends who had taken it in previous academic terms.

While students reacted positively to the integration of a genuine lab experience, some changes still need to be made in order to improve the course. It was found that the inverted pendulum lab was not achieving what it was intended to; while students found the inverted pendulum to be interesting, understanding the dynamics of an unstable nonlinear system posed significant challenges. Therefore, the inverted pendulum lab is being eliminated in the future. However, it is desirable to have something more sophisticated than the inertial disk. The velocity of the inertial disk can be described by first-order dynamics, since the inductance in the Qube is quite small, and the position is therefore described by a second-order transfer function. This means that some important control techniques, such as Ziegler-Nichols PID tuning, simply cannot be demonstrated using the Qube, since they require higher-order dynamics. Therefore, the lab instructors are considering creating custom attachments for the Qube; one proposed attachment, which is in the process of being designed, would include two rotational inertias with compliance between them, with an encoder to measure the position of the second inertia. With three energy

storage elements – two inertias and one compliance – this system would exhibit third order dynamics, opening up the potential for other laboratory experiments to be created. Other lab experiences, using other hardware, are also being considered for future development. This is an important issue for many universities; it has been the subject of study and development for quite some time,<sup>6,7</sup> and a number of different ideas have been the subject of recent publications.<sup>8,9,10</sup> Therefore, there is substantial material to draw upon. Since some universities have seen significant benefit from including items such as a wind tunnel<sup>11</sup> and fluid power components such as simple valves<sup>12</sup>, these types of lab experiences could be considered as well, particularly with a focus on equipment that is often used by the university's industry partners.

Since the students who have experienced the new version of the lab will not begin to graduate until June of 2015, the impact of the lab on students' performance in the workforce cannot yet be evaluated. Therefore, while it is believed that the lab revisions will address the concerns of the university's corporate partners, this cannot yet be determined. As students do begin to graduate, and as more students complete co-op assignments after taking the course, such an evaluation will be feasible and desirable. Results of this evaluation will be integrated into the continuous improvement of the lab experience.

In summary, while significant work still needs to be done, the redesign of the lab experience for MECH430 can be considered successful. Students find that the lab is a positive learning experience. Further development, informed by continuous evaluation of the lab's effectiveness, is expected to further enhance the experience and provide students with the skills and knowledge they need from the course.

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