Using Mechatronics to Develop Self Learners and Connect the Dots in the Curriculum

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Abstract

Mechatronics has traditionally been considered a simple combination of mechanical and electrical systems, but as technology and capability have advanced, the field of mechatronics has expanded to include mechanical engineering, electronics, computer engineering, and controls engineering. This multidisciplinary nature of mechatronics makes it an ideal basis from which to construct new capabilities and knowledge. As a mandatory senior level course for mechanical engineers at The Citadel, mechatronics is a course that allows students to exercise their creativity and problem solving skills in a multidisciplinary way. Upon entering this course, many students comprehend some basics of several of the constitutive disciplines, but now must work to integrate these areas while implementing new devices. This paper describes four hands-on labs that progress in difficulty. These challenges follow the course material and design, pushing the students to work through the lecture material and example problems. Students are encouraged to think about the final product they will present, and work towards implementing portions of it in each lab requirement. For those that adhere to this advice, the final integration is much easier than those who treat each lab as a disjointed exercise. Each lab requirement has at least one in-class work session, and two require the student teams to present their prototype or proof of concept. The faculty member who teaches the course and a lab technician are available to support the groups and provide additional information or assistance on implementing their devices. Student reviews (4.35 out of 5 on evaluations) and grades show they are meeting the desired learning objectives and enjoy the challenges (4.40 out of 5 on evaluations). Students with no prior programming experience in C++ quickly gain proficiency and are more confident with their critical thinking, creativity, and problem solving skills as well as their ability to be self-learners. Instructors report that the hands-on nature motivates students to achieve more than the bare minimum and be creative. Their imaginations and innovative solutions require the integration of introductory computer programming and microcontroller functions with electrical and mechanical engineering applications. Students mention the open ended, hands-on activities in the course feedback as relevant applications that helped them improve their understanding and appreciation for the theory learned in the classroom. Additionally, students have learned to incorporate some of the lab requirements into their senior capstone projects. Working through the labs provides an excellent vehicle for deeper understanding and solving open-ended problems while contributing to a number of ABET student outcomes.

Introduction

Industry has recognized the need for engineers with a multidisciplinary background and mechatronics education. Machines and manufacturing plants constantly grow in complexity due to increased customer expectations regarding their purpose and flexibility as well as expectations for shorter delivery times [1]. The need for engineering graduates, especially mechanical engineers, to study mechatronics has been emphasized at multiple levels over several decades. The ASME Vision 2030 [2] states that the problems that mechanical engineers work on often include elements of other engineering disciplines, require systems thinking in problem formulation and solution, and asserts that we must educate engineering students for a technological era of increased scope, scale, and complexity. Additionally, curricula must encourage and provide opportunities for active discovery-based learning. Brown, A. points out that mechatronic devices are all around us and argues that project leaders in industry should be those that understand other disciplines [3]. Given the hands-on and project based nature of mechatronics courses, many students are also interested and motivated to take these courses [4].

Today's students are usually very comfortable with technology, have shorter attention spans, a lower threshold for boredom, resist memorization and homework and favor action to observation [5]. Learning styles of these students are more visual and active rather than verbal. Given the characteristic preferences of these students, educators are exploring different and innovative teaching strategies that effectively address students in terms that they easily recognize and comprehend. For effective instruction to follow, educators should accommodate the needs of the learner. Brown, B. suggested that authentic learning requires the learner to communicate detailed understanding of a problem or issue rather than memorize sets of isolated facts, and must result in achievements that have relevance beyond the classroom [6].

One of the hardest things to do in our profession is to motivate and inspire students to learn. There are numerous examples of methods used to motivate students [7]. These various strategies include incorporating instructional behaviors, varying course structure, de-emphasizing grades, providing feedback, and emphasizing preparation, which provide many ideas on how to implement this new course. However, every teaching method has its advantages as well as its difficulties, so effective instruction uses multiple approaches. One noteworthy comment from Lang [8] was the conclusion that “comprehension lies outside of the classroom.”

Background

Students at The Citadel take an institution-wide core curriculum in liberal arts, math and science that comprises much of the first four semesters. For engineering majors, the majority of the courses in the remaining four semesters builds on this foundation in the discipline-specific engineering.

The approach taken by the Department of Mechanical Engineering begins with designing a multi-layered and dynamic educational experience for the students. The experience starts with exposure during the first year with different focus areas of mechanical engineering which includes a short block on mechatronics where students are exposed to the utility of computer-controlled electrical and mechanical devices. Freshmen also take a Matlab programming course, and routinely use Matlab in subsequent years. During sophomore year, mechanical engineering students take Statics, Dynamics, and a Circuits course in which students are introduced to the fundamental principles used in electrical engineering while also gaining practical experience creating circuits for a variety of practical applications, performing measurements, and simulating circuits using PSpice. During junior year, students take a Controls Engineering course which is a prerequisite for the Mechatronics course.

The mechatronics course is an introductory course, but taught at the senior level, involving the integration of mechanical engineering, electrical engineering, computer science, and controls engineering to simulate and design intelligent electro-mechanical systems. Nevertheless, each student has the necessary skill set to do well in this course and to learn how to apply practical analog and digital control to engineering systems. Students incorporate sensors, actuators, and electronic circuits to build such systems. While they focus on labs with a specific model microcontroller, the concepts learned give the tools to incorporate digital control in any project. Some students have prior experience with other microcontrollers and are allowed to use them as well.

Instructors and students often dislike solving simple textbook problems that have limited relevance to the real world. To increase student interest, creativity, and to promote the hands-on experience, open-ended labs were developed to foster problem-solving skills. This approach allows students to formulate and investigate their own realistic, inventive, and complex problems. This methodology has not only increased student enthusiasm, but has allowed many to further investigate a real world problem they had encountered or to implement new ideas into their senior design projects.

Originally, labs were not well developed and were very basic throughout the first year that the course was offered. In 2016, more emphasis was given to the lab experience, using just-in-time instruction to address key concepts and topics, given the breadth of the material. Students were required to complete exercises that reinforced material from the lectures and instructors gave them a demonstration of a solution as a preview of the actual lab activity. This sequence was repeated for each lab which strengthened their understanding of the material and helped make demonstrations go smoothly on lab day.

This course originally attempted to cover a wide range of topics with minimal deep learning from labs or hands on material. Caudron [9] suggested that educators consider the following five areas when teaching students, and many of these strategies are exemplified in the improvement of this class:

(1) Make learning experiential by engaging students in cooperative learning experiences.
(2) Give students control of their learning.
(3) Highlight key points since new learners are surfers and scanners rather than readers and viewers.
(4) Motivate learning by engaging students in their own learning environment.
(5) Challenge students to construct knowledge from their experiences.

Research Questions

One goal of the new mechanical engineering program is to identify best practices through assessment of the courses and program. Another goal of the faculty is to ensure the students have a positive experience in each course. STEM disciplines are traditionally taught by disseminating information and content, making them particularly fit for lecture [10], but in the case of this course, the instructors wanted to gage the students' opinions regarding the open-ended lab approach and evaluate how it impacted their learning. To assess these goals, students complete course evaluations after every semester, which assess for trends and opportunities to improve the course. These surveys include an institution-level survey to reveal student perceptions of the course and the instructor as well as a department-level end-of-course survey to show the evaluation of the course objectives. Overall, student evaluations of the course were very positive. Two questions the instructor wanted to answer include:

(1) Can student interest be influenced by a different lab approach in this mechanical engineering course?
(2) How well and will the students still meet course objectives with the new format?

In the past, the instructors observed that some students attempted to “pattern match” a specific solution on a previous lab and used these previous labs as resources, knowing the demonstration or experiment really did not change much from each offering. The goal of this new course structure is to encourage creative thinking over this pattern matching behavior.

Teaching Methodology

At The Citadel, a Mechatronics course was developed to teach subject matter required for the design of systems which have electrical, mechanical, and programmable aspects. A laboratory-driven approach was developed to bring together the different subjects and to relate classroom theory to real world application. Four laboratory exercises develop the students’ understanding of the material, reinforce prerequisite knowledge, and develop hands-on skills. Good teaching involves more than communicating the content of one’s discipline; a good teacher also needs both to motivate students to continue learning and to teach them the skills and strategies needed for continued learning.

Student teams of two were provided an Arduino microcontroller kit and various components to include basic sensors and actuators. Teams had to review lecture material, read component specification sheets and instructions, write program code to implement and calibrate the components, and answer questions about the actual lab. Most students had apprehensions about C++, knowing it would not be formally taught in the course. Less than 10% of the students had any C++ programming experience since most were only taught MATLAB as freshmen. With a few simple example codes and demonstrations, all students were able to teach themselves enough C++ for the first lab to minimize their anxiety for future labs. In fact, this demonstration of teaching themselves a new programming language is one of the embedded indicators for the program’s student (ABET) outcome to demonstrate lifelong learning.

Table 1 lists the Bloom’s Taxonomy levels exercised and the competencies developed by each lab. The overall design of each lab is based on the following structure:

1. Instructional content on a specific topic and the associated competencies.
2. Instructor examples that walk through step-by-step interactions with the equipment.
3. Demonstration of the student solution, explanation of the plan and problem statement, future enhancements, and a short question and answer session by the instructor or classmates to probe critical thinking skills.

Table 1 also shows the mapping of the different labs to the course objectives.

Table 1: Lab to Course Objective Mapping

Course Objective	Lab
***1. Comprehension* - Fundamentals:** Explain digital system components and demonstrate digital logic.	1-4
***2. Application* – Microcontroller:** Program and interface microcontroller devices.	1 – Light and Music Show
***3. Analysis* - Sensors:** Select and implement sensors to satisfy the performance requirements of a specified task.	2 – Sensors in parallel and series
***4. Analysis* - Actuators:** Select and implement actuators to satisfy the performance requirements of a specified task.	3 – Actuators in parallel and series
***5. Synthesis* - Design, Build, and Test:** Design and build a microprocessor-based or circuit-based mechanical system.	4 – Integrate sensors and actuators for a task

Students were required to have progress checks by the instructor at certain points in the lab to minimize frustration and costly damage of components. Many teams built systems that required components beyond their basic kits. The instructor either provided the additional components or redirected them to another solution. After students were comfortable with C++ programming, more than half of the groups sought larger prototyping boards, specific sensors and actuators, and even a robotic arm.

The question and answer session at the end of their demonstration gave a chance for other students to ask “what-if” questions to explore the concept further. On occasion, students in the audience offered suggestions and shared lessons from their own lab. The downside of this activity is that it took more class and lab time. It was a deliberate concession since it enabled deeper learning and sharing of ideas, but it reduced the amount of material included in the lectures since some labs extended into lecture periods.

Labs

The laboratory exercises were designed to give students experience with representative sensors and actuators and interface with analog and digital control circuits and microcontrollers. Additionally, the students were able to gain confidence in basic controller design and in using lab instruments. The course finishes in a microcontroller-implemented proof of concept to provide basic autonomy for an electromechanical device.

Lab 1 Requirement – Students make a music and light show by constructing a device that emits a signal in audio and visual formats with the lights synchronized to the music. They can select their own sheet music or request some from the instructor. They will need to convert the music notes into frequencies and durations for output to the piezo buzzer as well as have different LEDs or RGB LEDs signal when certain notes are played. They can use Arduino supplied codes for ‘Blinking an LED’ and the ‘Piezo Buzzer’ as demonstrations and learning the two separate tasks. Alternately, they can develop code and use other hardware.

Lab 2 Requirement – Students must decide which environmental conditions they wish to monitor and employ at least two sensors accordingly. In this lab, they employ two sensors simultaneously: Task 1 – sensors in series; Task 2 – sensors in parallel. No switches are allowed in this lab. Students indicate environmental conditions using the serial monitor or LEDs, typically. Students typically want to hardwire their sensors in series or parallel, but eventually understand they can control the response through simple logic and coding.

Lab 3 Requirement – Students must implement at least two actuators (servo motor, DC motor, etc.) in series and parallel and visually display the actuator output (position, speed, etc.) in an LCD or Serial monitor. The output can be varied through user input or by varying code. Here, students can see the power requirements of mechanical devices, especially when multiple devices are in operation.

Lab 4 Requirement –This laboratory exercise is an open ended project. The requirements are to integrate microcontroller code, at least two (2) sensors, and at least two (2) actuators in a mechatronic system. Students must use a combination of four sensors and actuators (two sensors and two actuators or more sensors and more actuators).

In all labs, each team must demonstrate the system and describe how it would be used in a real world application. The instructor grades them on their presentation, and a small number of their peers provide written comments back on their presentation skills. In addition to these demonstrations, teams submit a lab report (Outline in Appendix A) for grade. Labs 2-4 have the additional requirement to estimate the overall system reliability which reinforces the series and parallel differences when designing for redundancy.

Most student groups have no problems developing a scenario or real world application for their labs and may only need assistance in selecting a suitable sensor or actuator. The instructor usually helps some teams develop details for the problem statement so their implementation is more complete. The instructor also encourages them to think of the end product in Lab 4 before they start any of the labs. By working toward portions of a final product through Labs 2 and 3, students avoid creating totally new problem statements each lab and save time. Some teams have found an opportunity to implement part of their senior design project through these labs, knowing they were working on an electromechanical system.

Sample Integrated Projects

Some teams found real world problems that they experienced and wanted to solve by implementing what they were learning in class. This approach also provides ownership of the lab project and empowers the students to experiment and be creative with the system outside of the classroom.

Climate Control

After an HVAC failure in one of the student dorms over the summer, mold was detected, and Facilities emplaced hundreds of dehumidifiers and fans throughout the residence halls. One group implemented a ‘home climate control’ system. They measured temperature, humidity, and light level and actuated a stepper motor, DC motor, and LED. The user was able to adjust temperature and humidity limits to actuate the DC motor (fan speed) and stepper motor (the angle of the baffles within a 0 to 180 degree swing). The simulated fan provided airflow, and the baffles allowed the moving air to exhaust to the outside. The system can be adjusted to turn on automatically once a certain temperature or humidity is reached and can shut off once it gets below the desired temperature or humidity. An LED light is also integrated for night use and will turn on once the room light is shut off. Figure 1 below shows the sensor reading and Figure 2 shows their proof of concept solution.

```
Temp:85.37F, Humidity:33.28%
Temp:85.41F, Humidity:33.76%
Temp:85.39F, Humidity:33.90%
Temp:85.35F, Humidity:33.57%
Temp:85.34F, Humidity:33.25%
Temp:85.35F, Humidity:33.09%
Temp:85.39F, Humidity:33.10%
Temp:85.41F, Humidity:33.28%
Temp:85.43F, Humidity:33.37%
Temp:85.84F, Humidity:35.76%
Temp:85.93F, Humidity:41.23%
Temp:86.09F, Humidity:46.42%
Temp:85.91F, Humidity:46.80%
Temp:86.03F, Humidity:45.63%
Temp:86.17F, Humidity:49.05%
Temp:86.42F, Humidity:50.86%
Temp:86.34F, Humidity:53.72%
Temp:86.36F, Humidity:53.94%
Temp:86.28F, Humidity:48.31%
Temp:86.24F, Humidity:45.70%
Temp:86.22F, Humidity:43.90%
Temp:86.22F, Humidity:42.44%
```

Figure 1: Home Climate Control
Sensor Output

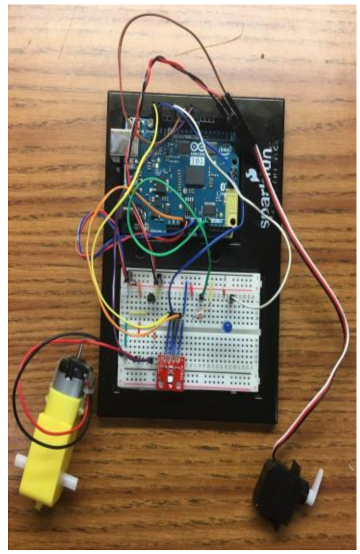

Figure 2: Home Climate Control
Proof of Concept

As part of the student demonstration some student groups opt to visually explain their devices as part of the peer-review. Figure 3 is a logic diagram for the climate control system that explains the sensors and accompanying actions. These student mini-projects could all be independent from each other, or for some of the more insightful students, they could build upon each other. Many groups chose to continue on with a theme and progressively elaborate each lab once they found an idea and were motivated to do more than a basic demonstration.

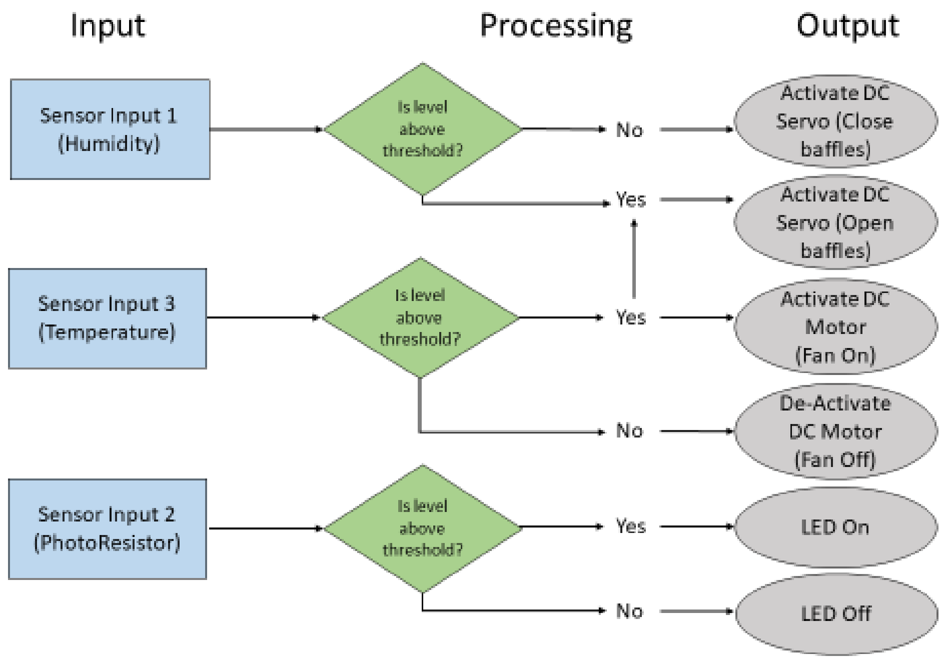

Figure 3: Student diagram and Explanation of the Climate Control System

Wastewater Wet Well Monitoring

While interning in the Wastewater Department with Grand Strand Water and Sewer Authority (GSWSA) a student was exposed to numerous systems within the wastewater collection process. From gravity-fed piping networks, to grinder motors, lift stations, the force main network, and lastly the treatment plant, the student not only developed a proficiency in the maintenance of these systems, but also learned how each one worked and the common challenges, demands, and inefficiencies with operating them. The purpose of lift stations is to act as a reservoir to connect local networks of gravity-fed sewage piping and then pump the wastewater into the force main, and on to treatment plants. At the bottom of the wells are pumps which are controlled by multiple float or probe sensors. Common problems triggered from float and probe sensors are control errors due to buildup of grease. Poor run times relate to one pump running longer than the other to lower the wastewater level back to the low state, most likely indicating that debris may be clogging the motor. Figure 4 shows a cross-section of a wet well.

With the second lab requiring the use of two sensors, the student decided to use an ultrasonic range finder and current sensor to operate in a useful method for lift station monitoring. The range finder would monitor the depth of wastewater in the well. The current sensor would monitor when and which pump was active and its current draw. Despite the student’s difficulty with coding the system’s operation, his intent was for the system to display the distance to an object (wastewater level) and the presence of an electrical field (pump on or off) onto a liquid crystal display. This simple scale model could be used as an improved automated control system for the lift stations. With a distance sensing device replacing the float system, the occasional need for an employee to report on site for cleaning would be eliminated. The students learned to apply the ultrasonic sensor with accurate results by following the data sheets and converting 'pings' to distance, knowing the speed of sound. From this, they could convert to inches or feet and set the threshold when the action would occur (pumping the well).

A similar system applied in the field with additional coding could provide live data of a wet-well's incoming and outgoing volumetric flow rate (depending on the state of the pumps), generate updated efficacy curves after each cycle, pump run times and power consumption, exact wastewater height and volume, historical trends of flow patterns, and even predict overflow time during a power outage to better prioritize asset deployment. The student plans to return to the GSWSA and present his scaled model.

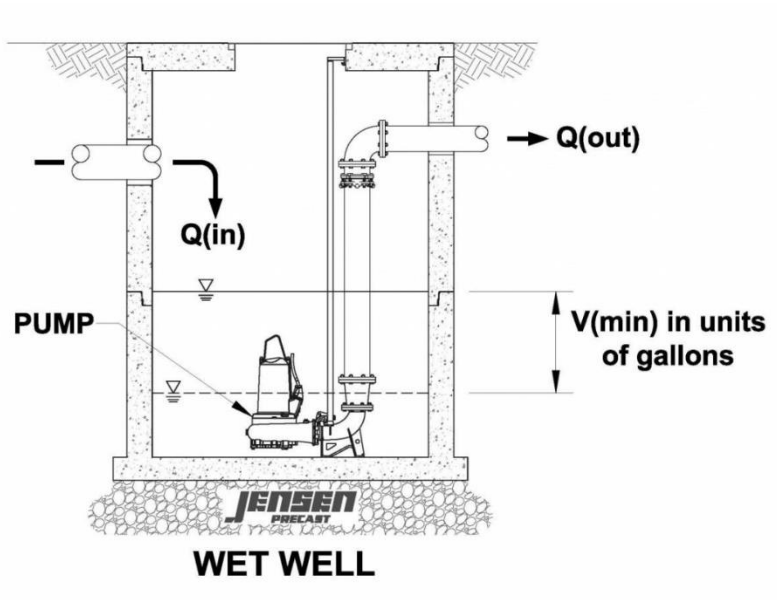

Figure 4: Wet Well

These two lab projects are just a sample of the many ideas the students developed for mechatronic applications. In addition to using their fundamental knowledge from several courses such as circuits and dynamics, many incorporated previous knowledge from other classes such as thermodynamics, fluids, and controls engineering in order to calibrate their systems. For instance, pump status (on or off) and capacity leads to power consumption, volumetric flow rate, and overall quantity of discharge. Once they were able to measure an environmental or physical parameter, students began to see possibilities for future applications and information.

Assessment

The assessment method included student end-of-course survey data that was collected during the last days of class and focused on measuring student's interest in the material and their assessment of meeting course objectives. The data from approximately 62 students who responded to the surveys was included in this study. A standard five-level Likert Scale was used to assess the level of agreement or disagreement for the questions (Table 2).

Table 2: Assessment Scale

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

The rating scale is a normal set of responses used at The Citadel for student surveys. Students and faculty alike are familiar with the same standard set of responses and their interpretation.

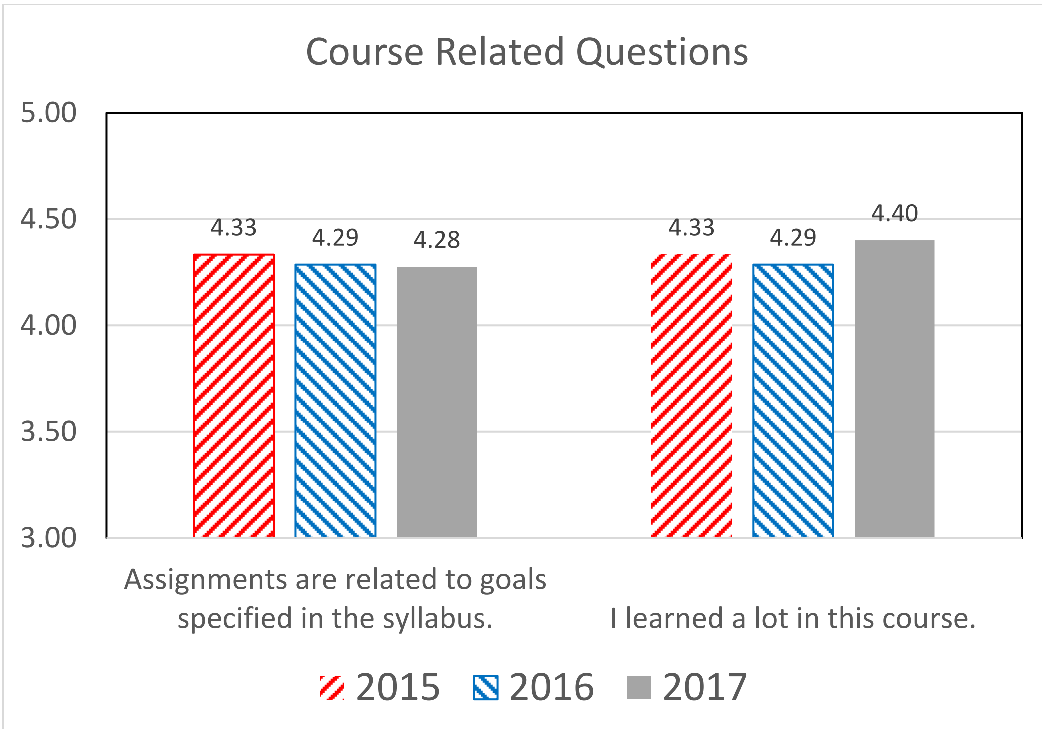

Figure 4: Course Related Questions

The first hypothesis examined by this paper is if student interest can be influenced by a different lab approach in this mechanical engineering course. Figure 4 shows a partial result of the course survey that asks course related questions. Additional survey questions addressed the course syllabus and grading system and are not included here. Overall, responses were very favorable ranging from 4.28 and higher on the Likert Scale. The highest score was the most recent offering in the area of "Learning a lot in this course."

Free text replies reinforced the favorable nature of the open ended labs and hands-on activities in the course. When asked what they liked about the course, typical responses included:

- I thoroughly enjoyed the lab component of this class. It offered a great opportunity to see the mechatronics process in action.
- Making actual things.
- The final lab combined all previous labs nicely.

- Hands on with the labs and coding in another language than MATLAB. Working with C++ was useful and I am going to use it in the future.

Most of the students feel that they are active learners and that they learn best by hands on activities. This is a good match for some of the methodology we have used to develop this course. Most students thought the real-world application allowed them to learn effectively and motivated them.

Using the scale presented in Table 1, Figure 5 shows that over three years of assessing course objectives, there is very good agreement on the students' ability to apply mechatronics theory to mechanical systems. Student comments and discussion on the student surveys reinforce their overall ratings.

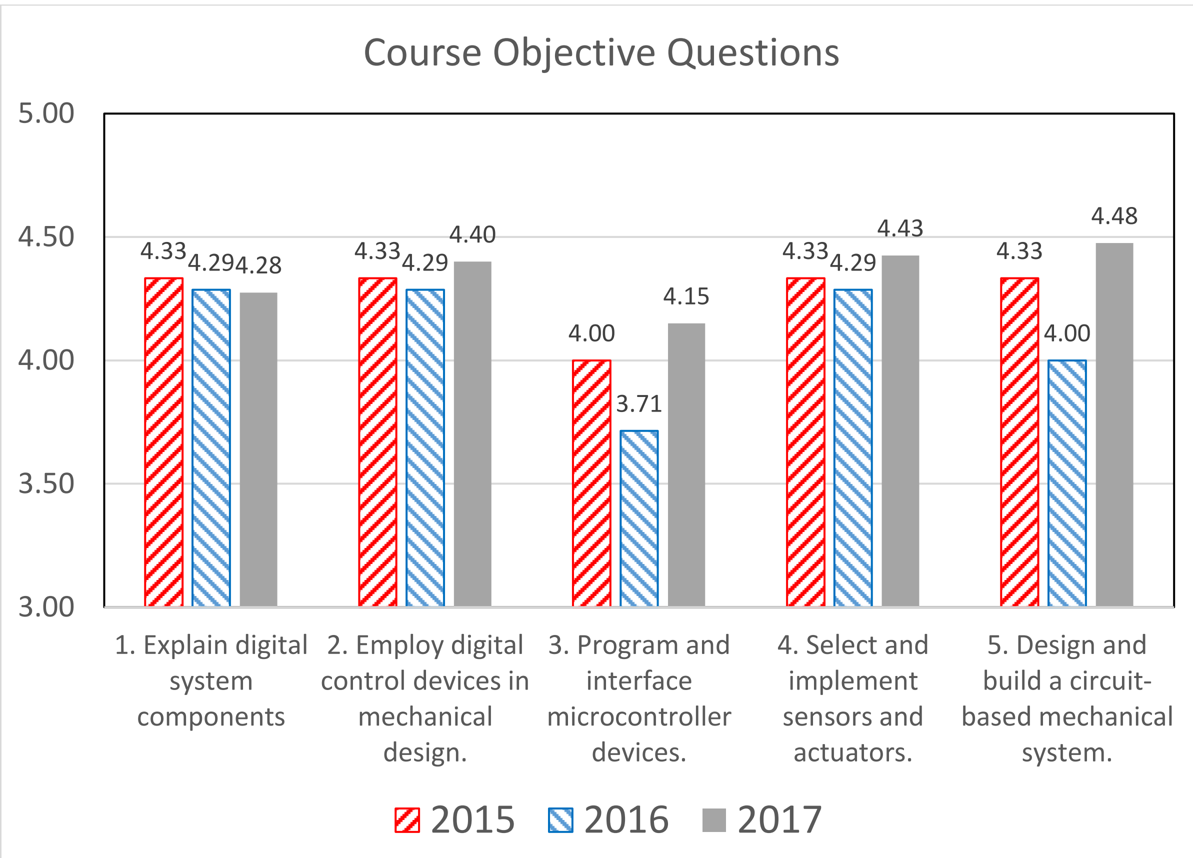

Figure 5: Assessment of Course Objectives

The second research question concerns student performance in meeting the course objectives. This question was answered with an assessment of the course objectives through embedded indicators. First, student performance in the form of graded events (or embedded indicators) is combined with a subjective faculty rating to produce an assessment of each objective in a course. The course director or instructor enters embedded indicator data after the graded event or at the end of the semester. The statistical data for each graded event is available from the instructors' gradebook. At the end of the term, all the entered data allows the overall average and standard deviation to be computed for each course objective and level of support by each embedded indicator. An analysis of data of student performance from many graded events can produce a detailed assessment of the course and areas for course improvement [11]. Figure 5 easily shows that students successfully met course objectives with a range of objective scores from 4.15 to 4.48 out of 5.0 on the Likert Scale. The highest improvement was in "Design and build a circuit-based mechanical system" which correlates to the previously mentioned hands-on nature of the labs.

Although all individuals had to demonstrate some proficiency with C++, teams usually had a stronger programmer, so some students did not consistently exercise programming skills. The only downward trend was "Explain digital control components" which is a result of the same delivery of the course's foundational material. The other objectives were clearly related to the open-ended labs and showed a positive change in all other objectives.

Some of the constructive feedback came from the question of what they liked least about the course:

- There are short deadlines for a lot of the assignments.
- Some of my classmates.

Conclusion and Future Work

This paper describes recent changes in a hands-on, laboratory focused course in mechatronics. The benefits of using real world problems of the students' choosing for the labs provide enthusiasm among students and faculty. Integrating basic mechatronic principles, microcontroller programming, sensors, and actuators allows a sequential process to develop a final project to support the students' interest. This drives student engagement, as they become invested in the projects that they develop, and the open-ended nature of the problems promotes the idea that students must continually strive to update their skills throughout their careers. This course structure reinforces the integration of these systems in a mechatronics course. However, students also used prior knowledge from other courses to demonstrate and explain their devices. As students were able to measure physical parameters, they began to see utility in their lab project and could easily find additional applications for their mini-projects. The short term goals are to evaluate existing course work and integrate more applications and demonstrations that could make an impact to the student's learning. There are many opportunities to improve the course, but initially focusing on the lab exercises has shown that teaching effectiveness can be improved. The careful selection of the labs promoted depth of student understanding and engagement that would not have been possible with a lecture-based course. The long term goal is to educate students on the employment and development of mechatronic systems to be used in future research and practical applications.

Employing real world problems and scenarios to make each lab different for each lab team is not easy or the right method for each lab-oriented course. However, this approach could stimulate faculty and students to approach other departments to conduct interdisciplinary research and conduct joint and collaborative design projects for other real world applications.

Multidisciplinary projects are also highly encouraged from the stand point of the departments but also very relevant and marketable for the student's future positions.

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Appendix A - Written Lab Report Deliverables

a. A **lab report** with the following sections:
   1) Introduction – Discuss the learning objectives/purpose of the lab.
   2) Materials – What items did you need to use for this report? You may need this to recreate the lab at another date.
   3) Methods – Explain what you did in experimenting with the base programs.
   4) Data – Is there any numerical data you recorded?
   5) Discussion – Discuss some of the key outcomes from this lab. Answer the questions below. Figures and graphs can be contained in this section. Pictures can be included to add clarity.
   6) Questions – See below for the separate Question Section.
   7) Conclusion – Sum up the lab in one paragraph.
   8) References – Reference any datasheets or other sources used in the lab.

b. **Questions** to address in the lab.
   1) How does your program work? (A brief, clear explanation is all that is required.)
   2) What is your base program doing? Hint, use / read the comments!
   3) What were the voltage and current conditions and the range of motor speed / position that you mapped or measured in the lab?
   4) How does the motor speed / position you observed compare to the nominal specifications given in the data sheet?
   5) Why does the motor not start immediately when voltage is applied?
   6) Describe a real world system that is equivalent to your device (actuator device)?
   7) Estimate the Reliability of your sensor system for the series configuration and for the parallel configuration. Use the actuator reliability estimates in the Table provided separately.
   8) What are the applicable industrial codes and standards (ASME, ASTM, ISO, etc.) for such a product you identified in the previous question?