"Just in Time" Mechatronics in Senior Design Capstones

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Abstract

Mechatronics was originally viewed as 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. Within the mechatronics course at The Citadel, many mechanical engineering students comprehend some basics of the mechatronic disciplines, but now must integrate these areas while implementing new devices for the labs. The suggested approach in the mechatronics course is a progressive project that builds on the previous iteration. Students can choose their own mechatronics application project. This paper briefly describes several hands-on labs that progress in difficulty. Students are encouraged to think about the final product and work towards employing portions of it in each subsequent lab. For those that follow this approach, the final integration is much easier than those who treat each lab as a new requirement. Student reviews and embedded indicators show they are meeting the desired outcomes and enjoy the challenges. Students with very little programming experience quickly gain aptitude and increase their confidence in critical thinking, creativity, and problem solving skills. In the course evaluations, students mention the open-ended labs as relevant applications in general and to their senior design capstone that helped them improve their understanding and appreciation for the theory learned in the classroom. Instructors report that the hands-on nature and project selection motivates students to be creative and accomplish more than the minimum.

Introduction

The coupling of electrical and mechanical devices is all around, from cars, smart homes, and to factories. Machines and industrial facilities constantly grow in complexity due to increased customer expectations regarding their purpose and flexibility [1]. Consumers desire features such as automatic controls and voice recognition. Mechatronic devices are all around and effective industry leaders will be those that understand other disciplines [2]. Many students are users of these devices and interested and motivated to take mechatronic courses, due to their hands-on and project based nature [3].

Mechatronics courses, by their broad nature, attempt to cover a wide range of topics with minimal deep learning from labs or hands on material. According to Caudron [4], educators should consider the following five areas when teaching students. Several of these strategies are exemplified in the improvement of this course and linking it to senior design projects:

- (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.

Capstone courses and projects are very important activities for student outcomes of an academic program. Capstone courses integrate and further build on the learning outcomes from many of the courses students study. Integrating mechatronics into a senior capstone design project is not always possible. However, much like a senior capstone project, mechatronics is a course that allows students to exercise their creativity and problem solving skills using project based learning and exercising teamwork. In this paper, sample capstone design projects using mechatronics and their outcomes will be presented. In particular, this paper gives an overview of the developed devices specifically by focusing on the design and development aspects of the prototypes. Mechanical Engineering students at The Citadel begin their senior year taking both the capstone course and the mechatronics course. Teams that may have a mechatronics application or subsystem in their capstone project are encouraged in the mechatronics course to develop part of it or demonstrate the proof of concept. This meets requirements for both courses and allows students to produce better capstone projects.

Background

Students at The Citadel take an institution-wide core curriculum in general education, 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.

For mechanical engineering students, the mechatronic experience starts with exposure during the first year in an Introduction to Mechanical Engineering course, which includes a short block on mechatronics where students are exposed to the utility of computer-controlled electrical and mechanical devices. The semester long 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 sequentially incorporate sensors and actuators into their electronic circuits. While they focus on labs with a specific model microcontroller (Arduino), the concepts learned give the tools to incorporate digital control in any project. Some students have prior experience with other microcontrollers (Pi, BeagleBone) and are allowed to use them as well.

To increase student interest, creativity, and to promote the hands-on experience, open-ended labs were developed to foster problem-solving skills. Instructors and students often dislike solving simple textbook problems that have limited relevance to the real world. 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 and 2017, 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.

One major goal of the 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 [5], but in the case of this course, the instructors wanted to gauge the students' opinions regarding the evolving 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.

In the first years of offering the Mechatronics course, the instructors observed that some students attempted to use old code and “pattern match” a solution on a previous lab and used these previous labs as resources, knowing the fixed lab really did not change much from each offering. In 2017, the instructors piloted a more open-ended lab format, but they were still prescriptive. In 2018 and 2019, the labs were fully implemented for students to build what interested them as long as they implemented enough components. Two goals emerged from modifying the course structure: 1) motivate students to synchronize mechatronic course activities with their senior design project where possible, and 2) encourage creative thinking over pattern matching behavior.

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. Rogers documented success with a similar approach of increasing rigor with successive experimentation [6].

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 extensively covered in the course. Typically, less than 5% of the students had any C++ or any other microcontroller programming experience. 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. After the first lab, most students were comfortable with coding challenges and knew how to find example code or programming commands.

Students had progress checks with the instructor at certain points during working sessions to minimize damage of components and to ensure teams were advancing. When 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, a robotic arm, and even pumps and relays. Student teams had to demonstrate each lab, which had a short question and answer session at the end of their demonstration, giving a chance for other students to explore the concept further. On occasion, students in the audience offered suggestions and shared lessons from their own lab.

Over the past two years, the Mechatronics course was offered in the fall terms with three and four sections, respectively, 67 and 86 students, and two and three different instructors each term. Section size was from 19-24 students each. Detailed lesson / lab meetings with the faculty ensured consistency and exchange of ideas to assist all students. As a teaching institution, no teaching assistants were available, so any help outside of class was from instructors and one lab technician. Students were able to get most or all components working properly in all the labs, so grading was based on complexity of the project, their ability make it work, and communicate their project scope and results. Details of the course logistics, grading, and feedback are a work in progress for a future paper.

Labs

The laboratory exercises were designed to give students experience with microcontrollers and integrating sensors and actuators to represent an actual system or a component of a large system. Additionally, the students were able to gain confidence in microcontrollers and calibrating both sensors and actuators. The course finishes in a microcontroller-implemented proof of concept to provide basic autonomy for an autonomous device.

Prelab / Project Proposal – Student teams must propose a mechatronic system that consists of at least two sensors and two actuators. Components must be different (e.g. cannot use two DC motors although their application may be different). Students should present a diagram of how the system works, and can modify it as they progress through the labs. Students should be able to identify basic sensors and actuators. This prelab allows the instructors to order more components if they are not on hand. Several student teams already had their senior design project assigned and proposed a subsystem of their project as the Mechatronics project.

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. The show must play for more than a minute and cannot be overly simple music, such as children's songs. 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 audio output as well as synchronize different LEDs or RGB LEDs with the notes and durations.

Lab 2 Requirement – Students must decide different measurands they wish to monitor and employ at least two sensors accordingly. In this lab, they employ two sensors simultaneously,

and demonstrate the system when both sensors work sequentially (series) and independently (parallel). Students indicate real time conditions using the serial monitor, LCD, or LEDs. Students must control the response through simple logic and coding.

Lab 3 Requirement – Students must further develop their concept by implementing at least two actuators (servo motor, DC motor, stepper motor, solenoid, pump, etc.) to 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 may employ a motor shield or driver when they see the power requirements of using multiple devices simultaneously.

Lab 4 Requirement – This lab was reworked to challenge the students with familiar concepts in an unfamiliar setting. Students are given a small robotic car chassis and motors, and can select their own sensors. They are required to have the car follow a wall autonomously, and can earn extra points for exceeding the required distance.

In Labs 1-3, 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, and reference industry codes for their system prototype, as well as estimate the overall system reliability to emphasize series and parallel differences when designing for redundancy.

Most student groups have no problems developing a 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 and help select components. The instructor also encourages them to think of the end product in Lab 3 before they start any of the labs. By working toward portions of a final product through Labs 1 and 2, students avoid creating totally new products for each lab and save time in the end. Even more significant is that some teams have found an opportunity to begin working on their proof of concept for their senior design project through these labs.

Results: Sample Senior Design Projects

For the students' senior design project, they develop a concept design and employ physical and mathematical modeling, analysis, computer aided design drawings, additional schematics if required, test results, and proof of concept in the fall semester. In the second semester, design teams refine the design, build, test, and present their product to multiple audiences. Some teams found that the progressive elaboration of the labs worked well for the requirements of their senior design project. They could implement what they were learning and developing in class with their proof of concept. Senior design is a two semester course, so those with an electromechanical senior design project had some additional benefit and motivation. This approach also stimulates pride and ownership of the lab project and empowers the students to experiment and be creative with the system outside of the classroom.

Traffic Solver

In this senior design project, students developed a traffic regulating system for construction zones. The “Traffic Solver” system uses two robot signs that can interact with each other through a computer code, using pressure sensors to count the cars as they enter and exit the work zone. When the vehicle runs over the pressure sensors, the weight of the vehicle will register and be tracked by the program. The number of vehicles in has to match the flow out in order for the signs to change direction and change the flow of traffic.

Users can also program a timer in the system. If a normal traffic light is about three minutes, one can set the system for that time, depending on the traffic flow on that road. There are also some safety features. For instance, if someone runs the stop sign and is going against the flow of traffic, it will register the count and turn both signs to stop while sending a signal to the construction site manager to warn them. The team has built a small-scale prototype (Figure 1) using toy cars but says it will be easy to build to scale. The team is confident that once the code is refined, it will be simple to build a bigger scale system.

The design could have other uses outside of construction work zones. It could also be useful in public safety, for hurricanes and other emergencies, especially to close roads and route traffic in one direction. If there’s a power outage, and traffic lights are inoperable, this system can be used at these locations, as well.

Figure 1: Traffic Solver Proof of Concept

Robotic Hand

Another senior design team is improving a robotic hand for sign language application. The team was tasked to add wrist and arm movements to spell particular letters. While taking the Mechatronics course, the team also wanted to improve the dexterity of the finger movements.

The objective of their speech interpreting robotic arm is to translate spoken English real-time into American Sign Language (ASL) as a teaching aid to augment teachers and interpreters.

Their additional degrees of freedom will make the robotic ASL easy to understand utilizing the aesthetics of a 3D printed human hand (Figure 2). Figure 3 shows the servo motors mounted in the forearm and undergoing testing and code validation.

Figure 2: Robotic Hand
for Sign Language

Figure 3: Servo motors in forearm
for the Robotic Hand

Other Senior Design Projects with Mechatronic Applications

The following short list is a representation of senior design projects where a particular subsystem of the project was matured partly through the Mechatronics course:

- a. Cartridge filter winding mechanism - a system for unwinding, cleaning, and rewinding string wound cartridge water filters used to treat water in developing countries.
- b. Inexpensive electric wheelchair - electric wheelchair, complete with speed and direction controls, capable of transporting a person over normal terrain.
- c. Wall crawling robot or UAV - Develop a robotic inspection platform. This includes the capability to (a) navigate and maneuver on a vertical structure, (b) collect data concerning structural health and quality and (c) store/transmit any important data to other robots or a base station.

- d. Robotic hexapod - Project is first iteration for a larger hexapod that can climb stairs and be used for recon and surveillance.
- e. Automated shed door - Redesign a metal shed into pet/livestock housing. Incorporate an automated door system that will open in the morning and close at night. Make it pet- and operator-friendly: safe for the pets and easy to operate and adjust for the owners.
- f. Solar Collector – optimize the orientation of the solar collector through a pan and tilt mechanism.

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 208 students over four years 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 1).

Table 1: 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 school for student surveys. Students and faculty alike are familiar with the same standard set of responses and their interpretation.

Figure 4 shows a partial result of the course survey that asks course related questions. Additional survey questions addressed the administration of the course (syllabus and grading system) and are not included here. Overall, responses were very favorable ranging from 4.0 and higher on the Likert Scale. The highest score was the most recent offering in the area of "Learning a lot in this course." Another notable improvement is in the area that "Many methods were used to involve me in learning." Here the large jump was in the first year (2018) to have open-ended labs in the course. In 2019, results were positive but not as high as 2018. The positive results are in agreement with previous researchers who incorporated lecture and laboratory materials in project based learning to better motivate the students to learn the material [7].

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:

- The labs were awesome.
- The labs and learning how to code.
- It ties a lot of different courses together.
- The hands on approach in class was much appreciated as it allowed for many different learning methods.

Figure 4: Course Related Questions

Most of the students feel that they are active learners and that they learn best by hands on activities. Most students thought the real-world application allowed them to learn effectively and motivated them. This matches well since some of the senior design projects were from real world clients and industry partners. Others have note the success of active learning strategies where students can see the direct use of the concepts from the course [8].

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

Figure 5: Assessment of Course Objectives

The second goal concerns student creativity and deeper knowledge over pattern matching behavior. An assessment of the course objectives through embedded indicators, can help determine success for that goal. Standard grading requirements (or embedded indicators) can demonstrate some proficiency. However, Figure 4 easily shows students' self-assessment of their success on course objectives with a range of objective scores from 4.40 to 4.58 out of 5.0 on the Likert Scale for the most recent offering of the course. The highest improvement was in "Program and interface microcontroller devices" which correlates to the previously mentioned active nature of the labs.

Although all teams had two individuals there was usually a stronger hands-on individual. Some students may not have consistently had to demonstrate some proficiency with C++. Teams usually had a stronger programmer, so some students did not consistently do hands-on work and focused on programming. The largest downward trend was in 2018 with "Design and build a circuit-based mechanical system." However, that was balanced in 2019.

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

- Go into more detail about learning Arduino language, there was a big learning curve.

- Add more fun products.

Students also had a healthy sense of accomplishment as their mechatronics projects were completed and carried into their senior design projects. Most were glad they had taken the course. The students learned independently how to obtain necessary information about specific sensors and actuators for their lab projects. One student group wrote in their lab report

Conclusion:

This lab experience was unlike those that we have done in the past due to the fact that the professor was very hands-off. Additionally, it was experimental and a learning experience lab rather than testing different situations and recording numbers. We found this lab very applicable to what many of us will be doing in the future and gave us good insight into what this course is all about. We began troubleshooting code from the very beginning which, when it comes to coding, is a valuable skill to have experience in.

Conclusion and Future Work

This paper describes recent changes in a hands-on, laboratory focused course in mechatronics. The benefits of using real world projects of the students' choosing and senior design problems for the labs provide motivation among students and faculty. Integrating basic mechatronic principles, microcontroller programming, sensors, and actuators allows a sequential process to develop a final project. This drives student engagement, as they become invested in the projects that they develop, and the open-ended nature of the problems reinforces the notion that students must continually strive to update their skills throughout their careers. This course structure reinforces the integration of these systems in a senior design course with a mechatronic system. However, students also used prior knowledge from other courses to demonstrate and implement their projects. By Lab 2, students began to see utility in their lab project and could easily find additional applications in their capstone and some real world applications. There are many opportunities to improve the course, but focusing on the lab exercises has shown that learning can be improved. The careful redesign of the labs promoted depth of student understanding and engagement that would not have been possible with a lecture-based course alone.

Employing real world problems and scenarios to make each lab project unique for each lab team has become easier with time. It is not easy to do flawlessly the first time nor is it the right method for each lab-oriented course. However, this approach could stimulate faculty and students to engage industry for project ideas or other departments for other real world applications. Multidisciplinary projects are also highly encouraged from the departments but also very relevant and marketable for the student's future positions.

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