AC 2009-1473: LEARNING MECHATRONICS THROUGH GRADUATED EXPERIMENTATION

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Learning Mechatronics Through Graduated Experimentation

Abstract

Mechatronics at the United States Military Academy at West Point is a senior level course that introduces the interdisciplinary design of smart systems. It is a central course in the robotics track of the electrical engineering program, and the centerpiece of the mechanical engineering program mechatronics track. Details of four hands-on activities that are graduated in difficulty are presented in this paper. The culminating lab utilized an unmanned vehicle. Relatively high speeds of the vehicle make the project fun and engaging. Instructors report that the hands-on nature motivates students to excel and be creative. Their often-innovative solutions require the integration of introductory computer programming and microcontroller functions with electrical and mechanical engineering applications. These unique interdisciplinary activities are designed to reinforce classical control theory learned in a prerequisite course. Students cite the hands-on activities in course feedback as relevant applications that help develop deeper understanding and greater appreciation for the theory learned in the classroom. Working through the experiments in order builds student confidence to solve open-ended problems in interdisciplinary teams. The initial assessments of our hands-on approach have been positive.

1. Introduction

At West Point, 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. Engineering mathematics, dynamic modeling of physical systems, Matlab / Simulink simulation, and teamwork are applied to solve several real world problems. The first activity is a resistance-heating thermal system with on-off control for temperature regulation. The second activity requires students to write program code to control a small robot. In the third activity, the students use classical control theory to stabilize an unstable magnetically-levitating steel ball. The fourth activity is the autonomous operation of a 1/12 scale electric-powered vehicle. Autonomy is achieved by adding a microcontroller to the system. The paper will also discuss our assessment and some areas for improvement for future course offerings.

Figure 1: Mechatronics students learn through hands-on activities.

2. Course Background

In 2003 the first interdisciplinary course was offered at West Point. Prior to this time, Dynamic Modeling and Control was offered to electrical engineering majors as EE471 and to mechanical engineering majors as ME471, but with essentially the same content. Driven by an institution-wide push to increase interdisciplinary study as well as a need to conserve resources in the small-college environment, the two academic departments collaborated to offer the course under a unified listing. Dynamic Modeling and Control is now listed in the catalog with an XE prefix rather than EE or ME and students from both disciplines are now together in the classroom. Mechatronics also followed this model. The students take pride in the XE designation; one was heard to say "we are eXtreme Engineers." This effort is not limited to math, science, and engineering; academic departments in the humanities and social sciences are also offering interdisciplinary courses.

Students at West Point take an institution-wide core curriculum in liberal arts, math and science that comprises the first three semesters. For engineering majors, the majority of the courses in the remaining five semesters builds the foundations in math, science and discipline specific engineering. Upperclassmen majoring in electrical engineering or mechanical engineering take a series of three courses that define a concentration for their studies. Mechatronics is the central course taken by students in their senior year who are concentrating in robotics or mechatronics. It is also offered as an elective to students of all other majors who have taken the two prerequisite courses, Dynamic Modeling and Control and Digital Computer Logic.

The Mechatronics course objectives are:

a. Fundamentals - Demonstrate breadth of fundamental mechanical and electrical engineering skills.
b. Sensors and Actuators - Select and implement sensors and actuators to satisfy the performance requirements of a specified task, and explain the role of sensors in measurement systems.
c. Modeling - Develop mathematical models that represent the governing physics principles of electromechanical subsystems and systems. Use computer models to predict the behavior of engineered systems. Compare predicted behavior to measured behavior.
d. Design, Build, and Test - Design and build a microprocessor-based- or electronic circuit-based-mechanical system.

When the course was first offered in 2007, class lectures were central and some demonstrations highlighted a few topics. Labs were not well developed and were very basic. In 2008, we used a laboratory teaching approach for this course with just-in-time instruction to address key concepts and topics given the breadth of the material. Students were required to complete pre-lab exercises that reinforced material from the lectures and in turn gave them a preview of the actual lab activity. The pre-lab assignments strengthened their understanding of the material and helped make experiments go smoothly on lab day.

3. Mechatronics Teaching Methodology

Four laboratory exercises were developed for the Mechatronics course. These activities give the student hands on experience with systems that combine mechanical, electrical, and programmable aspects. The labs support the course objectives in the following ways. The labs:

- implemented sensors and actuators to satisfy requirements of specific tasks;
- required students to mathematically model system dynamics from basic principles;
- simulate the system with a computer model; and
- design, build, and test a physical electromechanical system.

The course was designed beginning with the labs; the development of lecture material and homework assignments followed so as to provide the students the appropriate theoretical foundation. Further, we integrated MATLAB, Simulink, and a Basic Stamp microcontroller into this course. The students applied knowledge from Engineering Mathematics, Circuits, and Dynamic Modeling and Controls courses into their controller designs.

4. Laboratory grading

Pre-lab assignments were individually graded so students were encouraged to prepare for each lab by completing these assignments. The pre-labs variously required the students to review lecture material, write program code, read component specification sheets and instructions, and answer questions about the actual lab. Experiments were conducted by teams of two or three students; each team member earned the same grade on the jointly-written lab report. Students were required to have quality checks by the instructor at certain points in the experiment to minimize the frustration and potential costly damage of mistakes. At certain less-critical points, teams were allowed to have a quality check by a classmate from a different team, reducing bottlenecks when one or two instructors handled several lab groups. For the final project student teams were required to demonstrate their project before the instructors and classmates. Also for the final project each student was given an oral exam by the two instructors. Points awarded for team effort were balanced with points for individual achievement to maximize project accomplishment without leaving individuals behind.

5. Laboratories and Projects

The laboratory exercises were designed to give students experience with representative sensors and actuators and interface with analog control circuits and microcontrollers. Additionally, the students were able to gain confidence in basic controller design and in using lab instruments. The semester culminated in a microcontroller-implemented controller design to provide basic autonomy for a small unmanned ground vehicle (UGV).

Each lab exercise will be discussed; the learning objectives and expected cognitive achievement according to Bloom's Taxonomy[1] are listed in tables in the Appendix. Objectives marked with an asterisk require students to apply hands-on skills.

Lab 1: Thermal System On-Off Control. The purpose of this lab was to introduce a simple mechatronic system with a sensor, feedback, and an actuator. Figure 2 shows an block diagram of the main components. Students demonstrated familiarity with the instruments in the lab –

oscilloscope, arbitrary waveform generator, and triple power supply. The apparatus consisted of a coil of copper magnet wire with an embedded thermocouple temperature sensor. The coil served as a thermal actuator. Students used mechatronics principles to assemble a simple on-off controller to keep the heating element temperature within a specified band. Figure 3 illustrates the heating and cooling cycle of the thermal actuator, visualized through the oscilloscope. Students interpret the rising and falling slopes of the oscilloscope trace; the steep rise results from heating while the electrical current is flowing through the actuator, and the falling slope results from natural convective cooling.

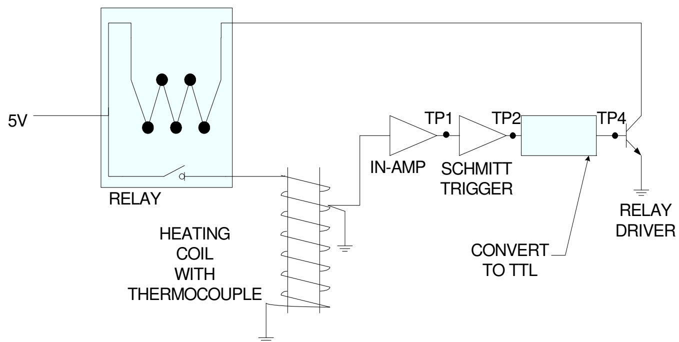

Figure 2: Thermal System Block Diagram

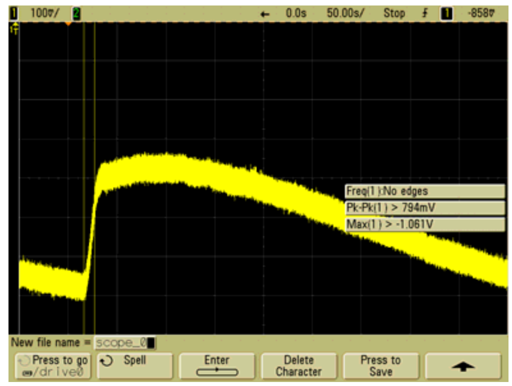

Figure 3: Heating and Cooling Cycle

Lab 2: Robot Balance beam. Students were required to interface a Memsic 2125 Accelerometer with a SumoBot and write Basic language program code. The task is to construct an autonomous vehicle to find the highest point on a hill. The hill was modeled in the lab as a balance board, so that the vehicle would find the center of balance and stop or stay within a margin to keep the board balanced like a see-saw, Figure 4. The vehicle would start at the end of the unbalanced board and climb on the see-saw which simulated uneven terrain. The Basic Stamp Editor from Parallax[2] was used to program the BS2 Microcontroller.

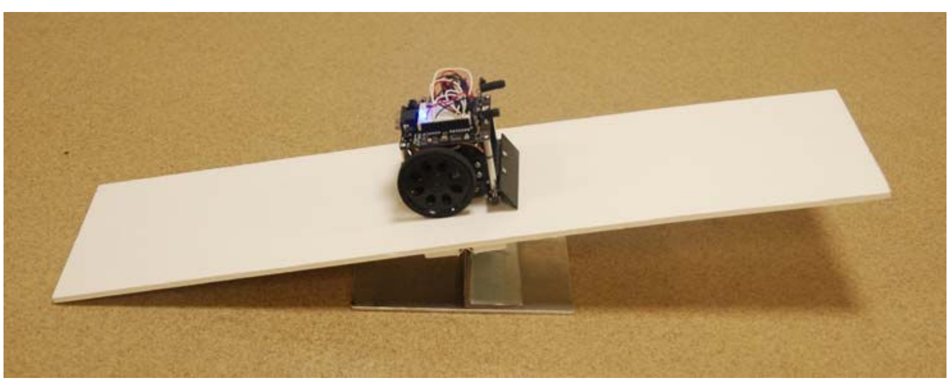

Figure 4: SumoBot Balancing on a Dynamic Beam

Lab 3: Magnetic levitation controller to introduce analog control. The task was to build an analog feedback controller to stabilize an unstable system. Figure 5 shows the completed system working; the steel ball is suspended in mid-air. Figure 6 illustrates the functional elements of the system. Students clearly enjoyed this achievement. The governing equation for the steel ball in equilibrium is derived from Newton's Second Law where magnetic force and weight act in opposite directions. The magnetic force is modeled as proportional to current squared divided by gap distance squared:

$$m\ddot{x} + c\left(\frac{i^2}{x^2}\right) - mg = 0$$

where m is the steel ball mass, x is the air gap between steel ball and electromagnet, $\ddot{x}$ is the acceleration, c is a proportionality constant reflecting the strength of the magnet, i is current, and g is the acceleration due to gravity. Students must linearize the equation of motion to the following form which reinforces material the students have learned in the prerequisite, Dynamic Modeling and Control:

$$m\ddot{\hat{x}} = c\left(\frac{2\bar{i}^2}{\bar{x}^3}\right)\hat{x} - c\left(\frac{2\bar{i}}{\bar{x}^2}\right)\hat{i}$$

The overbar (¯) represents the known quantity at equilibrium, and the (^) indicates the perturbation about the known quantity. Class lectures teach the students how to obtain a transfer function model of the plant from this linearized equation. The transfer function for position with respect to current can be obtained:

$$\frac{X(s)}{I(s)} = \frac{k_1}{s^2 - k_2}$$

Where k_1 and k_2 are constants calculated from measurable properties of the system. Once the transfer function of the system is known, the students can design PD or other compensators to stabilize the system.

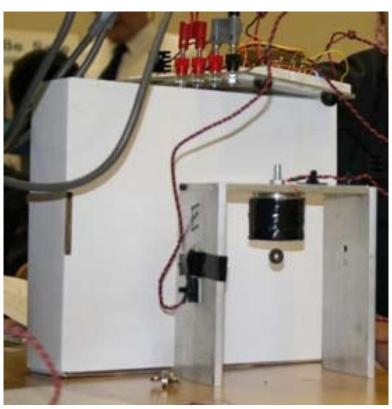

Figure 5: Magnetic Levitation in action

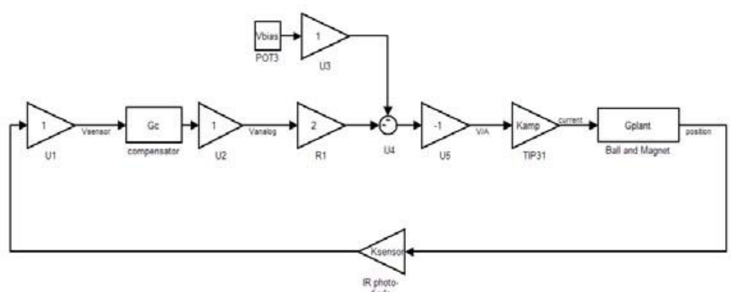

Figure 6: Magnetic Levitation system closed loop

Lab 4: Autonomous Unmanned Ground Vehicle using ultrasonic sensors and feedback. The UGV was chosen as the culminating activity for four reasons:

- mechanical, electrical and programmable skills are required in one system;

- the system strikes the right balance on the spectrum of complexity—not too easy and not too difficult;
- the students enjoy it and are thus motivated to learn; and
- some students are likely to work with these systems after graduation.

Each student team was provided with a Traxxas E-Maxx[3] radio controlled vehicle, Figure 7, with the task of developing autonomous control for specified requirements on a course with obstacles. The course instructors named the vehicle Traxbot.

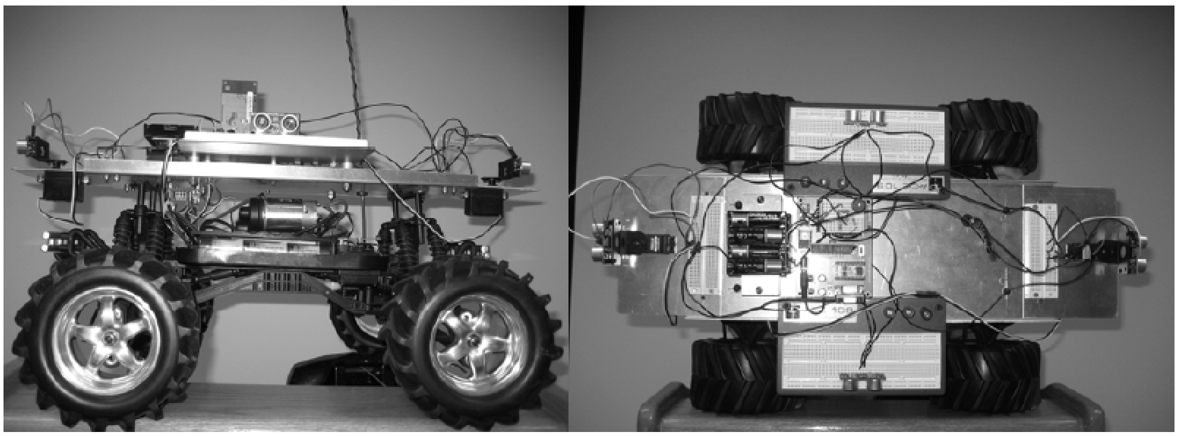

Figure 7: Traxbot

Students had to write, implement, and debug a well-documented Basic Stamp program for the Traxbot that would:

a) Follow a wall using the ultrasonic sensor approximately 120 cm away from the wall
b) When the wall is uneven, the Traxbot can adjust and continue to follow the wall, 120 cm away from the wall

When there is an obstacle in front of the Traxbot, it will stop 30 cm away and play an audible signal on a speaker, Figure 8.

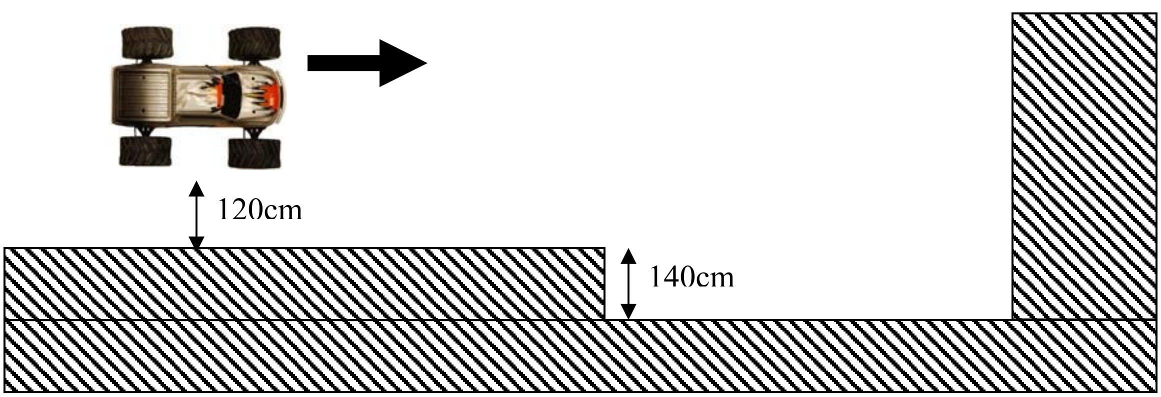

Figure 8: Course layout (diagram not to scale)

6. Progression of Laboratory Objectives

The four labs increase in difficulty, and each successive lab builds upon the objectives of prior labs. For example, the use of the instruments learned in the first lab is required throughout the semester. Implementatin of direct digital control in lab two is required on lab four. The level of cognitive achievement of the lab objectives is illustrated in Figure 9. Each data marker on the chart represents the classification according to Bloom's Taxonomy of the lab objectives. These are ordered from left to right on the chart as they are met during the semester. This senior-level laboratory-based course is designed such that the majority of the objectives are classified as application or analysis.

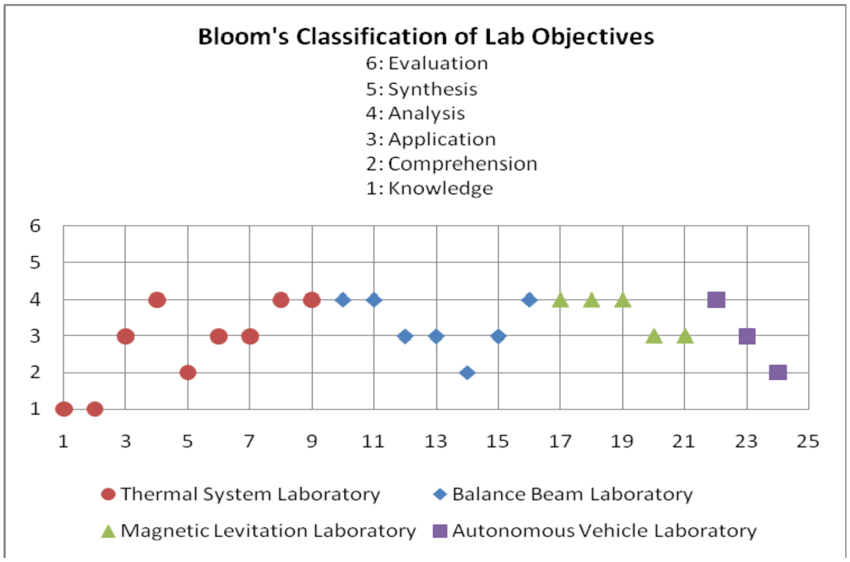

Figure 9: Cognitive Level of Lab Objectives

7. Assessment

The course was assessed using student course feedback and course director / instructor assessment of specific assignments. One of the instructors' goals was to assess the effectiveness of the new laboratory approach to the course material. A look at the course feedback data from students taking the Mechatronics course the past two years shows some interesting and encouraging results (Figure 10). Spring semester 2007 (AY 07) consisted of 9 students, and Spring 2008 (AY 08) consisted of 13 students. For the most part, the AY08 students agree that the course is a positive experience for them, much better than the previous year's course where labs were very basic demonstrations of mechatronic principles. Students tend to rate this course higher overall than single-discipline courses. Although different instructors taught the course over the academic year, individual instructor assessments were very similar, so the overall course results are presented. Only particular ratings that are addressed in this paper are included on the charts. The following scale (Table 1) was used for the students' survey:

Table 1: Assessment Scale

1	2	3	4	5
strongly disagree	disagree	neutral	agree	strongly agree

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

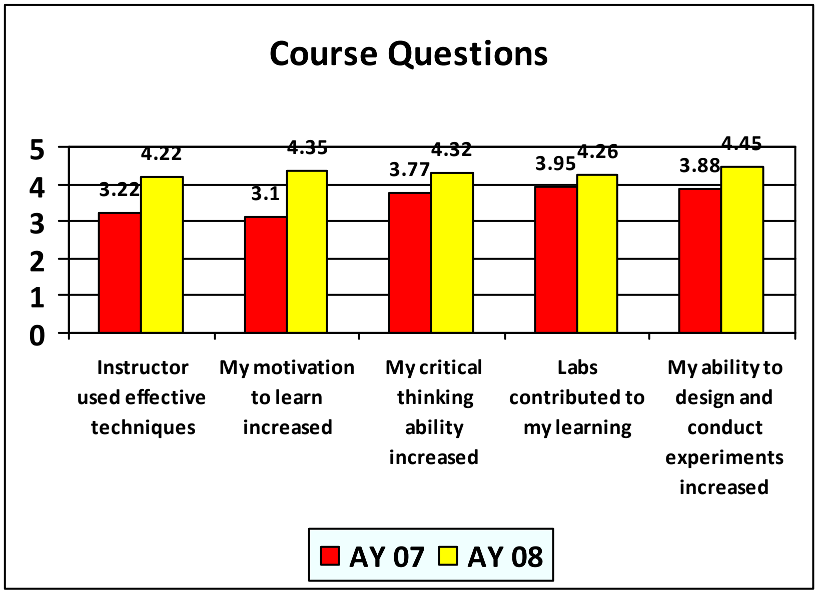

Figure 10: Course Questions (n=9, n=13)

Using the same scale presented in Table 1, Figure 11 shows that over two years of assessing course objectives, there is very good agreement on the students' ability to apply mechatronics theory to mechanical and electrical systems. Student comments and discussion on the student surveys reinforce their overall ratings. One benefit of relating the material to both engineering disciplines is that a larger number of students may retain the material longer than if the material was taught from just one of the disciplines. Learning styles do not make as much difference as the student's prior knowledge, intelligence, and motivation[4]. The course is currently in its third year; the data of Figures 10 and 11 are for the first two offerings. The authors feel the multi-department faculty model and structure of the course are advantages; quantitative assessment of this structure is under way. The first course objective (Demonstrate fundamental mechanical and electrical engineering skills) was included last year and was not assessed in 2007.

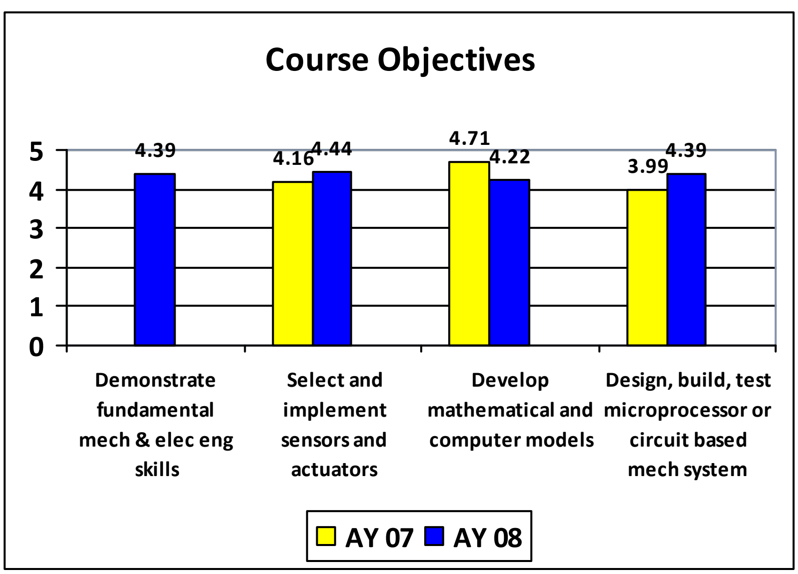

Figure 11: Course Objectives (n=9, n=13)

8. Contributions and Future Work

Mechatronics is a senior level class designed to achieve objectives of analysis and application through progressive lab activities. Labs begin with the basic use of lab instruments and culminate in an open-ended mechatronic design. Assessment shows that this hands-on class solidifies knowledge and skills acquired in prior classes.

Multidisciplinary engineering courses could stimulate faculty and students to approach other departments to conduct multidisciplinary research and conduct collaborative design projects. Multidisciplinary projects are highly encouraged by the departments and help the students become more knowledgeable and valuable in their future positions. Describing the advantages and limitations of the mechatronics course as a multidisciplinary teaching endeavor provides a catalyst for the development of other courses.

The short term goals are to evaluate the existing course content and integrate more labs and demonstrations that could make an immediate impact on the students' learning. For instance, student feedback has indicated the second lab with the Sumobot on the balance board was not challenging enough. Students wanted to work more on the Traxbot. This student feedback has produced a new electronic speed controller lab using the Traxbot and will replace the Sumobot lab. These improvements will better prepare our future engineers to take a multidisciplinary approach to solving problems that exist today[5-7].

9. Conclusion

This paper summarizes a hands-on, laboratory focused course in mechatronics. The benefits of sharing applied engineering and math, dealing with various dynamic engineering systems, learning through generalization of problems and applying mechatronics principles provide enthusiasm among students and faculty. There is ample opportunity to improve this course in many areas, but focusing on the lab exercises has shown that teaching effectiveness can be improved. The careful selection of the labs promoted depth of student understanding that would not have been possible with a lecture based course. Teaching a broad multidisciplinary course requires a committed, motivated faculty who are creative and willing to work together, but the benefits are worth the effort.

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Appendix – Laboratory Objectives

Table 1: Thermal Systems Lab	
Objective	**Cognitive Level: Bloom's**
Read an electronic schematic diagram	Knowledge
List common integrated circuits used for amplifying low-level signals	Knowledge
Assemble a circuit from a schematic diagram*	Application
Use electronic lab instruments to produce, measure, and classify waveforms*	Analysis, Knowledge
Describe the function of each sub-circuit in a more complex electronic system	Comprehension
Practice check-as-you go strategy for assembling complex circuits	Application
Build a closed loop system with an actuator and a sensor	Application
Use electronics laboratory instruments and methods to investigate and explain unexpected behavior*	Analysis
Use an oscilloscope to interpret the behavior of a mechatronic system*	Analysis

* Objectives requiring application of psychomotor skill

Table 2: Robot Balance Beam Lab	
Objective	**Cognitive Level: Bloom's**
Use laboratory instruments to characterize the input-output relationship of a sensor*	Analysis
Use laboratory instruments to characterize the input-output relationship of an actuator*	Analysis
Follow instructions to assemble a microprocessor-based closed loop system*	Application
Interface sensors and actuators with a microcontroller*	Application, Comprehension, Knowledge
Explain direct digital control	Comprehension
Develop microcontroller program code to implement direct digital control	Application, Knowledge
Distinguish between inefficient and efficient program code	Analysis

Table 3: Magnetic Levitation Lab	
Objective	**Cognitive Level: Bloom's**
Characterize the input-output relationship of a nonlinear sensor*	Analysis
model and predict the behavior of a nonlinear physical system	Analysis
Propose a simplified model of a complex system	Analysis
Design an analog controller to stabilize an unstable system	Application
Assemble a system stabilized by an analog controller*	Application

Table 4: Autonomous Unmanned Ground Vehicle Lab	
Objective	**Cognitive Level: Bloom's**
Design a microcontroller-based system incorporating sensors and actuators to satisfy a set of requirements	Analysis, Application
Assemble, test and troubleshoot a complex system*	Application
Demonstrate project performance to class*	Comprehension, Knowledge