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Work In Progress: A System-Level Approach for an Introductory Mechatronics Laboratory Course for Undergraduate Mechanical Engineering Students

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Abstract

Mechatronics is an interdisciplinary engineering field that involves knowledge across mechanical, electrical, and software engineering. In general, undergraduate engineering programs teach mechatronics as individual topic labs that then request students in developing a full system-level mechatronics semester project utilizing skills of design, manufacturing, and electronics. This lab format may not provide effectively the necessary learning skills to perform system-level integration and debugging for multidisciplinary problems that are typically encountered in a mechatronics project. This paper shares the development of an introductory laboratory curriculum that teaches mechanical engineering students to gain fluency in electronics and software with system-level demonstration to be a valuable employer of mechatronics. When we talk about systems, we use the NASA Systems Engineering handbook definition as "a construct or collection of different elements that together produce results not obtainable by the elements alone." This is the mindset we want students to carry throughout the mechatronics curriculum. To focus on the practical applications of mechatronics, we developed a lab curriculum that cultivates system-level thinking around the build and integration of a hypothetical NASA Mars rover project. Overall, the course aims to teach students analog/digital sensing technologies, actuation hardware, Proportional-Integral-Derivative control, and microcontroller software implementation from a system-level teaching approach ensuring cross-functional debugging skills for each lab. This approach can be advantageous towards students completing their semester project in the design and development of their own mechatronic system.

Introduction

From agricultural to space exploration, mechatronics is an important branch of engineering for understanding and solving complex multidisciplinary problems. The engineering workforce has demanded more of engineers acquiring mechatronic skills as our society expands for more integrative technical products and services [1]. For instance, products in related areas of biomedical devices, industrial automation, and autonomous vehicles require the diverse engineering skills that a mechatronics curriculum can provide. The justification for mechatronics education development in engineering degree programs have garnered the importance for the next generation of engineers [2, 3].

A robust mechatronics curriculum can generally span across several undergraduate courses [4]. This allows students a gradual climb to gaining proficiency in acquiring multidisciplinary skills, which overcomes the steep learning curve encountered within mechatronics. However, most mechanical engineering undergraduate programs cannot fulfill a mechatronics course series as it removes other important areas within a broad discipline such as mechanical engineering. For undergraduate institutions offering a mechatronics lab course there are different instructional approaches to covering a widespan of the different discipline areas within mechatronics. Such curriculum can provide a prebuilt, custom designed mechatronics system board or mobile robotic system that students interactively learn upon to become familiar with sensors and actuators [5]. Though, this can be costly in providing a large class set size, while also removing too much low-level design understanding for these prebuilt units needed to realize high-level learning goals. The design of a system from the ground up with debugging and troubleshooting along the way is how students can gain the skills typically required in a final semester mechatronics project. Others have developed mechatronics curriculum within mechanical engineering programs that emphasize around mechanical design giving students a familiar base to work from, and slowly easing them into the software and electronic skills [6]. This approach was effective and showed positive student feedback, however it focused much around mechanical design; a skill mechanical engineering students develop with or without a mechatronics course in their degree program. Our proposed course intends to bring mechanical engineering students up to speed with the necessary electronics and software skills to handle system-level tasks generally found in mechatronics. Students are encouraged to leverage the mechanical design skills they have gained in other courses for their semester project. Furthermore, the lab curriculum proposed in this paper is partnered with a semester mechatronics lecture course that meets two days per a week that students must enroll concurrently with the mechatronics lab. All lab material will have the concepts covered during lecture to give students the necessary knowledge and tools to complete what is requested of them prior to attending their respective lab session.

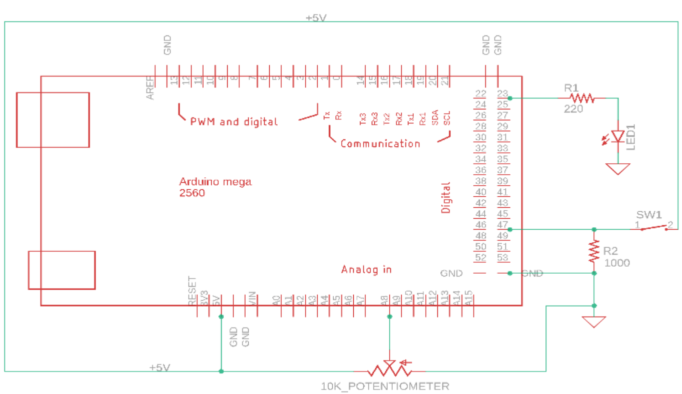
Mechanical engineers tend to serve as the role of systems engineers in various industries, such as in aerospace or automobile, and it is viewed as a growing need to integrate system-level thinking in engineering education [7]. System engineering is an integrative discipline where factors contributing from mechanical, electrical, and software engineering are evaluated to produce a balanced functional system [8]. This paper proposes a series of labs that are designed to reinforce the interdisciplinary nature of mechatronics by creating five labs that revolve around a system-level approach. A system-level approach requires students to combine techniques from a breadth of engineering disciplines in order to meet multiple system design requirements. One of the major goals of this system-level approach is to develop more robust cross-functional debugging skills in mechanical engineering students. To achieve this, we have designed each lab to involve the integration of an electrical system, software system, and often an electro-mechanical system. While integrating these systems you are likely to encounter issues such as circuit power constraints, electrical sensor signal integrity, microcontroller processing limitations, or simply software producing flawed results. We hope debugging and troubleshooting these situations often during these labs expands the variety of problems our students feel comfortable in tackling. In conclusion, the labs span in covering an introduction to electronics hardware and microcontrollers, digital and analog sensing technology, IR detection and navigation, motor drive/control, and Proportional-Integral-Derivative (PID) control implementation on a physical system. To reduce the rigor of embedded systems programming for mechanical engineering students, the Arduino Mega has been the chosen microcontroller as an open-source platform with readily made online learning material that is commonly used in mechatronics curriculum [6].

Approach

The curriculum has a focus on cohesive student learning outcomes culminating to an introductory basis of mechatronics knowledge. The proposed curriculum is compartmentalized into five labs, each with their own learning outcomes that will contribute towards students' ability to design and fabricate a final mechatronics project. Narrative scenarios have been incorporated for each lab to give a sense of a real-world application that establishes system-level problems to be solved while providing a means to engage students on a popular society mission such as space exploration. The overarching scenario of the lab curriculum is to have students be part of a NASA Mars rover team as a systems engineer, where each lab activity they work on the design, build, or integration of a subsystem for the rover [9]. To help students prepare, they are provided with a prelab assignment as an introduction and review of the necessary subject matter for each lab. The prelabs request students to design pseudocode and circuit schematic as well as simulate their circuit prior coming to lab to understand expected results prior to working the actual hardware. Pseudocode is a text-based technique for outlining the creation of your software as to avoid unnecessary logical error in your actual code. This allows viable lab time to be spent on hardware/software integration and debugging with an instructor on hand. The five labs are given the first 7 weeks of the semester with the remaining 9 weeks students dedicate time to their semester project. The labs are described below.

Lab 1 - Introduction to Lab Equipment, Electronics, & Microcontrollers

The first lab does not introduce the NASA scenario as it introduces the necessary lab equipment and microcontroller for circuit design and debugging to aid for the remaining lab assignments. Students learn how to operate an oscilloscope, power supply, function generator, and digital multimeter (DMM) that gives an understanding for their usage in operating and debugging electronic hardware throughout the semester. The prelab requires students to create the lab 1 light emitted diode (LED) circuit schematic with microcontroller using computer aided design (CAD) software, such as open-source platform Autodesk EAGLE [10], and develop pseudocode that describes the Arduino microcontroller software flow to aid in developing the actual software code to complete lab 1. An example of the prelab completion is given in Figure 1.




```
Arduino Pseudocode

Program_initialization()
BEGIN
        SET LED pin as output
        SET POTENTIOMETER pin as input
        SET LIMIT_SWITCH pin as input
END

Infinite_loop()
BEGIN
        READ POTENTIOMETER voltage
        WAIT if limit switch pressed

        IF (limit switch pressed)
                Turn Off LED
        ELSE
                Turn On LED
                GET delay function with Pot as input
                Turn Off LED
        ENDIF
END
```

Figure 1 – Lab 1 Prelab Assignment: LED and Microcontroller; Circuit Schematic (LEFT) and Pseudocode (RIGHT)

Furthermore, students are to review the electrical datasheets of the components used in order to appropriately size them to the circuit and perform circuit simulation with an open-source tool, such as LTspice [11]. For example, this lab's circuit design would involve finding the current rating of the LED and sizing an appropriate current limiting resistor (Figure 1). The remaining prelab assignments follow this format of preliminary hardware and software design requirements to better prepare students for the lab's main content.

A common task when introduced to microcontrollers with hardware is to write code that flashes an LED light on and off [12]. It similarly represents to developing the program "hello world" for embedded systems programming [13]. This first lab is a system-level take on this classic problem, while providing a well-rounded introduction to electronics lab equipment and microcontrollers. We begin by powering an LED connected to a +5 Volt low current power supply in series with a low constant resistor and potentiometer as a variable current limiting resistor that varies the current through the circuit. Using a DMM they can measure the changing current, voltage, and resistance in the system. Next, we have them power the LED with a function generator to output to three different waveform signals between a sine, square, and triangle low frequency waveform. This allows students to observe a visual change in the LED output based on a different type of electrical input. Furthermore, an oscilloscope is used to measure the output of the function generator to provide a secondary visual to the electrical signals. Next, students move forward to understanding the behavior of their LED system. This system uses a potentiometer resistor acting as a variable speed adjuster to change the waveform frequency at which the LED flashes. Reading the potentiometer requires turning its electrical output into a signal the microcontroller can interpret by using an analog to digital converter port [14]. Furthermore, a limit switch (see Figure 1) that when pressed will turn off the LED and stop it from flashing. Reading the limit switch requires understanding how to use general purpose digital input/output pins on a microcontroller to read a voltage that is switching from a high to low state. Lastly, the lab requires the students to learn how to setup trigger states using an oscilloscope, to catch quickly the electrical state change such as the voltage transition that occurs when pressing a limit switch. Oscilloscope triggers are a valuable debugging tool to utilize when working with circuits and microcontrollers. We hope introducing these concepts early allows students adequate time to learn about designing and integrating with these tools and equipment.

Lab 2 - Digital and Analog Sensing for Terrain Navigation

Lab 2 is the first lab that introduces the NASA Mars rover scenario by having students develop a system that measures force to get feedback while pushing around rocks, detect falling objects such as debris, and activate a motor that translates the rover to escape the falling objects. This is a two-week lab assignment that teaches students about processing analog and digital sensors differently in software. It also introduces electrically controlled switches and electric one-way valves, such as transistors and diodes, respectively.

Students are given a prelab assignment that entails developing a preliminary circuit and pseudocode relating to the lab, similar to Figure 1. The lab begins with using a force sensitive resistor (FSR) analog sensor circuit that reads the change in voltage depending how much force is applied onto the FSR. Then students are to take the FSR voltage readout and create a visual indicator using an LED bar graph for outputting the amount of force being measured across the FSR sensor range. They will also have an analog proximity sensor, where students will learn about signal conditioning with an integrated circuit component called a comparator with hysteresis. A comparator allows us to compare two input voltages and outputs either a high or low voltage, depending on a define threshold [15]. This transforms our analog sense reading to a digital output, which students are then introduced to a microcontroller software tool called an Interrupt Service Routine (ISR). This teaches students to understand software flow in a system and how one can interrupt the flow of the program to operate other block of code [16]. Students are to implement an ISR that triggers when a proximity sensor detects a specified distance set by the comparator circuit to then operate a motor flyback diode drive circuit for unidirectional control [17]. In conclusion, these interactive tasks provide the system-level thinking for mechatronic students to solve the NASA Mars rover scenario introduced as part of this lab.

Lab 3 - Infrared Detection and Homing Beacon

In this lab, the NASA Mars rover mission narrative continues by having students develop an infrared transmitters and receivers for the purpose of navigation, to enlighten students this system problem on Mars not having a satellite network that supports Global Positioning System. The lab has the students detect various infrared transmitters flashing at specific frequencies and compute the operating frequency of these infrared beacons that help lead the Mars rover to a specific navigating pathway.

In the prelab, students use an infrared LED, a light sensitive phototransistor, a comparator, and use lab equipment (see Lab 1) to design the IR transmitter and receiver circuits. The phototransistor is a transistor switch activated by being exposed to infrared light as opposed to an applied base voltage. Since we can activate our circuit with IR light, we essentially have a rudimentary means of wireless communication. The comparator circuit from Lab 3 is revisited to turn the phototransistor output into a well-behaved digital high and low voltage signal as seen in Figure 2 below. Using this well-behaved high/low voltage value, we have students write software to calculate the frequency of the comparator output. Although, not entirely necessary students can leverage their new knowledge of interrupts from Lab 2 to make this frequency determination more efficient. They will display the frequency by printing to the Arduino IDE serial monitor. The Arduino serial monitor is a means to display information from compiled code and is an invaluable tool when designing and debugging software.

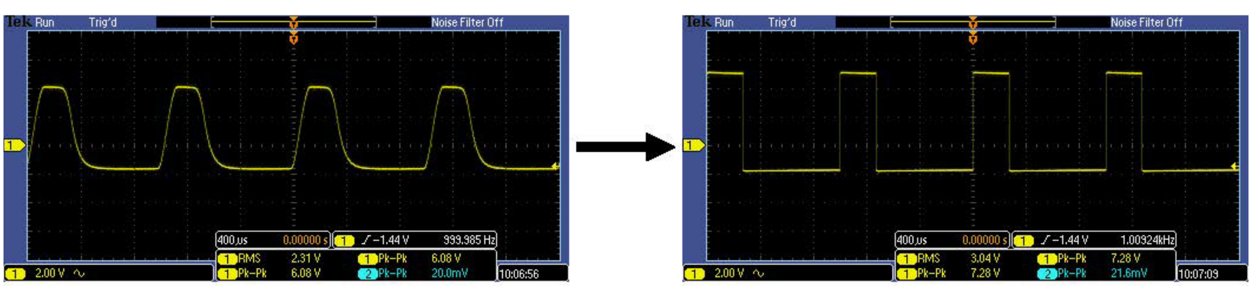


Figure 2 – IR Transmitter/Receiver Phototransistor Output (LEFT) versus Comparator Final Output (RIGHT)

Lab 4 – Motor Drive Modes for Optimized Maneuverability

The next task for the NASA Mars rover narrative is to design a means of moving the rover in various directions and speeds according to feedback from an ultrasonic sensor to measure proximity distance of incoming objects. Students are provided a laser cut fabricated chassis to mount motor wheels and various hardware. Students will also learn the importance of having a dedicated power supply for high power devices such as motors [18].

In this lab, we introduce how to achieve motor speed and direction control using an H-bridge and pulse-width modulation (PWM). PWM is a technique in which the power delivered to a system is the average of discrete signals [13]. The lab has students setup an ultrasonic sensor to measure distance, then depending on the distance being measured the PWM frequency will adjust as the motor should either speed up, slow down, or switch directions. There are also three motor drive circuit modes that students will investigate; drive brake, drive coast, and lock anti-phase drive modes as well as their relevance trade-offs in motor performance [17]. This lab provides students immediate understanding of how an outside indicator such as an external sensor can change the operating conditions for motion control of a motor.

Lab 5 – Closed-Loop Feedback Control System

The last portion of the NASA Mars rover narrative has students work on a Proportional-Integral-Derivative (PID) controller to control motor speed to simulate fine control precision to the rover. This system is used to emphasize the need for closed-loop systems in mechatronics. Closed-loop systems use sensor feedback in order to confirm that the system is operating at a desired set point [19]. The goal is to confirm that the motor is or is not running at a given set speed. If not, we must adjust our system in order to drive as much error between the desired and actual speed towards zero as seen in Figure 3 below. The students spend effort in software coding the PID controller architecture to the microcontroller for control tuning.

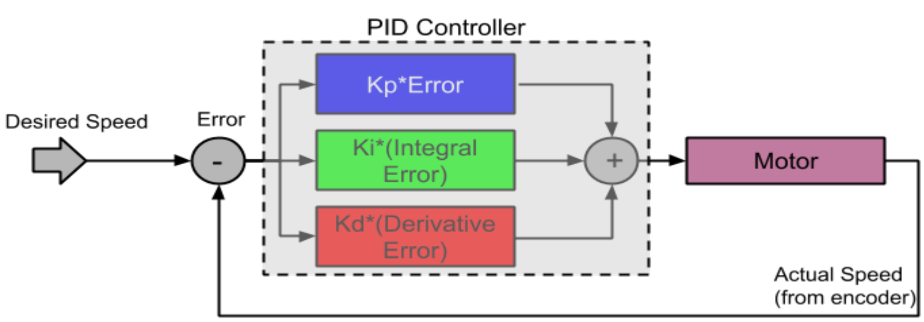


Figure 3 - PID Control Block Diagram

Students are to process a digital rotary encoder output to calculate the speed and direction of a motor. Both the given desired motor speed and actual motor speed is printed to the Arduino serial monitor of the motor response to be saved to a text file. The data is imported into Mathworks MATLAB and using the system identification toolbox they are to create an estimate for the system transfer function of the motor [20, 21]. Using the estimated transfer function, students are asked to use MATLAB's PID tuner application to tune the control gains as control systems engineers are known to utilize for system-level control. Although, PID controllers can be an advanced controls topic for an undergraduate feedback controls course, it can be valuable to begin understanding the basics for controlling a first-order system, such as a motor, as a simple but practical example for an introductory mechatronics lab course.

Course Timeline and Learning Skills

Table 1 gives the new learning skills expected each week as the trend reduces as labs progress. The rationale behind this is to give them a large number of basic concepts early to then actively learn how to use them for the later labs. As students continue to progress through the course, many of the concepts continue to be applied, deepening one's understanding of each concept, as well as adding on new concepts from subsequent labs.

Table 1 - Student Learning Skills from Labs 1-5

Lab #	Student Learning Outcomes
Lab 1	Electrical: Voltage Dividers, Potentiometers, Current Limiting Resistors, LEDs, Limit Switches, Oscilloscope, Power Supply, Function Generator, Digital Multimeter Software: Polling, Analog to Digital Converter, Digital/Analog Input/Output Pins, Software Delays, EAGLE, LTspice, Arduino IDE
Lab 2	Electrical: Analog Proximity Sensor, Comparator, 5 Segment LED Display, Force Sensitive Resistors, Transistors, Diodes, DC Motor Software: Interrupts, Serial Monitor
Lab 3	Electrical: Infrared LED, Infrared Phototransistors, Pull-Up/Pull-Down Resistors Software: Interrupts with timing constraints
Lab 4	Electrical: H-bridge, DC Motor, Ultrasonic Sensor Software: Pulse Width Modulation
Lab 5	Electrical: Rotary Encoder Detection Software: System Identification toolbox, PID Control

After having built an adequate collection of mechatronics knowledge from different system-level tasks, students will begin to develop the final project of the course. The specific project may change each semester, but will always employ the student learning skills from each of the labs. A list of potential semester projects is given in Table 2. Students will form into small groups, two to three students, which will be assigned the same project and objectives. Each team will have the freedom over the system design and choice of components to fulfill the project requirements. After an allotted time, demonstration of working subsystems will have had to be completed to ensure steady progress towards meeting the project milestones. The teams will have approximately 9 weeks to accomplish this project.

Table 2 - Potential Final Projects

Battle Bot Competition	Each group design a robot that will locate and remove an opponent from an arena whilst remaining within the arena boundaries.
Basket Bot Game	A robot is designed to locate a goal post from IR sensor detection and either place or launch a ball into a goal post with teams competing against each other.
Arcade/ Carnival Games	Final project will be a playable game complete with scoring and autonomous reset. Games must differ between student groups.

To better understand just how much time is to be allocated for the course tasks, Table 3 provides the given weeks across the semester and when assignments are due.

Table 3 - Tentative Course Timeline

Week #	Assignments
Week 1	• Lab 1: Introduction to Lab Instruments, Electronics & Microcontrollers
Week 2/3	• Lab 2: Digital and Analog Sensing
Week 4	• Lab 3: Infrared Detection and Homing Beacon
Week 5	• Lab 4: Motor Driver and Drive Modes
Week 6/7	• Lab 5: Closed-Loop Feedback Control System
Week 8	• Form final project group members • Brainstorm project design
Week 9/11	• First draft of mechatronic design • Present design concept to instructor for review • Finalize mechanical and electrical design • Create build of materials and order parts
Week 11/12	• Begin project fabrication and testing
Week 13	• Low-level subsystem demonstration due
Week 14	• High-level subsystem demonstration due
Week 15	• Finalize project build for full functional demonstration • Prepare for final presentation/competition
Week 16	• Final presentation/competition

This proposed curriculum is in its early stages, where like many education research in mechatronics lab curriculum a course survey is to be provided for feedback in order to gauge our success [22]. This proposed survey will allow analysis for how much students learned from the course, how engaged they were, and if they felt amount of material learned was reasonable. Refer to Appendix A.

Conclusion and Future Work

This course should provide mechanical engineering students to integrate new knowledge between electronics and software necessary to be a mechatronics engineer with system-level thinking. The material has been structured in such a way that students can work through each lab and walk away learning new skills beyond their fundamental mechanical engineering curriculum. For our student evaluations, we predict to see an increase in student engagement and understanding from having a real-world application they are solving, such as a NASA Mars rover mission. Moreover, the proposed mechatronics curriculum should provide students to encompass more challenging mechanical engineering senior design capstone projects that most students are taking concurrently or the following semester of taking the mechatronics course.

In the future, we have many aspirations for growing the mechatronics curriculum. After receiving student feedback from this course and improve the curriculum based on that feedback, we would like to develop a mechatronics course series that allow students to receive a mechatronics minor to add concentration to their education before graduation. The course series may address advanced mechatronics course topics such as embedded programming, process automation, and wireless networks.

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Appendix A

Course Survey

Rating Scale Questions:

1. The procedures for the lab were clear and easy to follow. ____
2. The prelab helped prepare for the work to be done in the lab. ____
3. Lab procedures and expected learning outcomes were relevant and valuable. ____
4. I feel comfortable using electronics datasheets to understand how components work. ____
5. I had all the resources and materials I needed to complete my tasks. ____
6. I learned new and exciting material in an in-depth manor. ____
7. I received appropriate help in a timely manner. ____
8. The course has improved my problem-solving skills. ____
9. This course helped me to become a better systems engineer. ____
10. I feel more comfortable dealing with electronics and circuit analysis by the end of the course than I did in the beginning of the course. ____
11. I feel more comfortable dealing with software design by the end of the course than I did in the beginning of the course. ____
12. This course was useful in obtaining knowledge of the mechatronics/robotics field, and I am now more interested in the field. ____
13. If available, I'd like to take a graduate level course in mechatronics. ____

Open-Ended Questions:

What was your biggest frustration while taking this course?

To what extent did your work in this lab course help your academic performance in courses linked to the lab?

What would you have liked to see more of in this course?

What comments/questions/concerns do you have for this course?