Electric Vehicle Circuit and Electrical System Senior Lab Project

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Abstract

As part of a multidisciplinary team, electrical engineering students worked with computer and mechanical engineering students to create a small-scale electric vehicle. The major tasks of the team were design and performance prediction; fabrication of the vehicle, control circuits, and computer data acquisition board; system integration and testing; racing the vehicles against other teams; and comparing performance data to predictions. This paper will discuss the electrical engineering students' design efforts for the project. The project enhanced student learning and provided a practical approach to multidisciplinary teamwork. In addition to the design, build, and test tasks typical of the engineering design process, electrical engineering students learned about Failure Mode and Effects Analysis (FMEA) and how to design circuits to provide for safe outcomes when portions of the system fail. The paper provides an overview of project; describes the learning objectives, as related to the electrical engineering aspects of the project; describes the FMEA process; and includes detailed descriptions of the circuits in the appendix.

Introduction

Western New England University has a long history of incorporating engineering design into laboratories and courses. 2012 marks the university's 50th annual capstone design effort. Additionally, interdisciplinary team efforts are initiated in the freshman year and continue for all four years[1]. This paper describes the electrical engineering aspects of one of the interdisciplinary lab exercises that occurs during the senior year fall semester. In the latest implementation of the class, electrical engineering students were introduced to Failure Mode and Effects Analysis (FMEA) as part of the design process.

Project Description

During the fall semester at Western New England University, students enrolled in computer, electrical, and mechanical engineering senior lab courses worked together to design and produce a prototype electric vehicle. The vehicles were fairly small, typically 5 to 10 pounds and less than 2 feet long. The power source was a rechargeable 12.8V $LiFePO_4$ battery pack that had a 3000mAh rating. For safety, a battery pack with built in electronics was chosen. The protection included: overcharge, over discharge, a 7A current limit, and short circuit. The vehicle was designed to complete a drag race and figure 8 race. The drag race course is about 100 yards along a road that has around a 10 foot elevation gain. Each of the three disciplines had specific design, build, and testing tasks. During the semester, students from the disciplines worked together to integrate their designs.

The mechanical engineers designed, built, and tested: the chassis, drive train, suspension, steering, and breaking systems. The computer engineers designed, built, and tested a data acquisition system that collected: vehicle speed from a beam break sensor and analog voltages representing the motor current and battery voltage. The computer engineering board also provided an enable signal to the electrical engineering student's circuit board; together the boards enabled or disabled the motor. The electrical engineering students designed, built, and tested a control circuit that acted as a current governor for the motor. The remainder of the paper will focus on the efforts of the electrical engineering students.

Electrical Engineering Current Governor Circuit Design Overview

During the first week of the project, teams were formed and students were given an overview of the project. After the interdisciplinary group meeting, each set of students met with the professor in their discipline. The electrical engineering students met weekly for two 1.5 hour lab sessions. During these labs, aspects of the design were covered. The current governor consisted of five parts. First, a triangle wave generator and open-loop pulse width modulator (pwm) was covered. Second, a current sensor and an amplifier with a 4^{th} order low-pass filter was covered. This circuit converted the current into a voltage representation of the average current flowing through the motor. Third, a differential amplifier and a Proportional + Integral controller was covered. Fourth, a potentiometer interface / amplifier circuit was covered. Finally, a FET & Flyback diode circuit was covered. A representative schematic is attached in the appendix.

After the students built breadboard prototypes of each circuit, they began to design their circuits for the vehicle. In order to complete the design, build, and test cycle in about 9 weeks, portions of the control circuit were given to the students. The triangle wave generator and open-loop pwm circuit, the FET & Flyback diode circuit, and the diff amp and PI controller circuit designs were given to the students. The 4^{th} order low-pass filter, the potentiometer interface circuit, and the failure mode and enable circuits were designed by the students. The project had some important specifications. Most notably for safety and current capacity of the FET and Flyback diode, the motor was allowed 0A to 4A average current. The DC gains of the 4^{th} order low-pass filter and the potentiometer interface needed to be matched in order for the command and feedback circuits to work correctly together. Students also needed to design in some flexibility to adapt to the mistakes in the mechanical system. For example, the servo that turns the potentiometer may not turn the potentiometer enough or may turn it too much (the potentiometer was the input to the command portion of the circuit). In these cases, the potentiometer interface circuit would require a gain adjustment to keep the motor current command signal in the proper range.

Course Learning Objectives and FMEA

In the course, there were many learning objectives that students mastered to varying degrees. Table 1 lists the objectives and what items were measured to assess how well the students achieved each objective. Many of the objectives are used in the department's assessment of ABET a-k outcomes[2]. Because the scope of this paper is limited to the electrical engineering aspects of the project, this paper will focus solely on the objectives related to the electrical systems and the FMEA aspects used to teach robust design. The last three learning objectives: teamwork, written and oral communication, and societal impact are not covered in this paper.

The first learning objective was an ability to design circuits to solve open-ended problems. For this objective, students were given a motor to test to determine the characteristics of the current flowing through the motor. Figure A9 (in the appendix) shows the circuit used to test the motor's characteristics. When the motor current was being controlled by the PWM signal, the motor current characteristics were determined mostly by the frequency of the oscillator that controlled the PWM timing. For this project, students used a signal in the 1kHz range. A second set of tests were performed to determine the motor current characteristics when the motor was driven at 100% duty cycle. Here, the motor was connected to a generator that had a variable load. This allowed the students to test the motor with different loads in order to see the how varying the motor torque effects the motor current with regard to amplitude and frequency. After the testing was complete, students needed to design a 4^{th} order low-pass filter and amplifier that would convert the motor current into a DC voltage representing the average current flowing through the motor. Most students chose a Sallen-Key 4^{th} order filter with a DC gain of 20V/V. Students were given a specification of 10mVpp ripple for the output of the filter when the motor had an average of 4A flowing through it.

After the filter/amplifier was designed and tested, students needed to determine the proper gain for the potentiometer interface circuit. Here students were told work with the mechanical engineers to determine a rotation range for the potentiometers that were driven by a radio-controlled (RC) servo motor. The teams were supposed to work together to reach agreement on a common design such that all the potentiometers would rotate the same amount. The reason for this constraint was to make all of the electrical engineers' circuit boards compatible with any of the vehicles. Students were taught that common design allows for interchangeability. If one team's circuit board failed they could borrow a circuit board from another team and still allow their team to compete in the race. During the race, two cars competed against each other in each heat. During the past iteration of the project, the teams did not cooperate to determine a common rotation range; there were 3 different ranges between all the teams. So, some compatibility was preserved but a few teams did not have another circuit board compatible with their vehicle. For the most part, students performed well in these open-ended design tasks. The average assessment score was 3.5 on a 4 point scale.

While the next two learning objectives were largely subsumed by the first learning objective, there are some subtle differences. The ability to collect data and analyze the results was comprised mostly of the filter/amplifier and potentiometer interface design, but also included converting raw data, collected during or before the race, to physical units. Here only about 2/3 of the students performed well. The average assessment score was 2.3. Problems with the mechanical systems delayed the race by a few weeks and students had less time to write their reports. This led to many reports being weaker than reports from previous years – many students presented results with voltages from the A/D and did not convert the A/D voltages back to the correct unit or scale.

The ability to test and debug circuits was exercised heavily during the project. Students built their circuits on breadboards and then transferred the circuits to prototype boards where connections were soldered. While most of the mistakes were open circuits and adjacent pin short circuits, there were also occasional broken wires, cold solder joints, and incorrect components. All of these problems afforded a great, albeit painful, opportunities for students to hone their debugging skills. What most of the students gleaned from the experience is that one must truly understand what the signals should look like when a circuit is working properly in order to determine where the circuit ceases to operate correctly. Because the circuit was a closed-loop feedback system, it was often difficult for students to determine the cause of the problem. They learned to decouple the circuit sections and test each section separately to determine where the circuit was not working. Learning to break a problem down into its components is a valuable lesson for students to experience before they enter graduate school or the workforce. An example of one failure is shown in Figures A6 and A7. Here, the student used the wrong value for a capacitor and caused the current governor to oscillate while the control circuit maintained the proper average current. Typically the controller will oscillate in the range of 15 to 30 Hz for this failure mode.

Table 1: Course Learning Objectives and Assessment Methods

Course Learning Objective	Assessment Technique
An ability to design circuits to solve open-ended problems.	Motor Characterization memo, Filter design and Pot interface design memo, FMEA
An ability to build, test, debug circuits.	Circuit testing results and final report
An ability to collect data and analyze the results.	Motor Characterization memo, Filter design and Pot interface design memo, race results analyzed in final report
An ability to work on an interdisciplinary design team.	Instructor Observation and summative team surveys
An ability to communicate effectively in written form, in team design reviews, and in formal team presentations.	Weekly team oral progress presentations, final report, final presentation
An ability to understand the impact of energy choices upon the societies of the world.	Report on effects of electric vehicles on the electrical grid loading and on pollution

The FMEA process was conducted for the first time in this course during the fall 2012 semester and focused on connectivity failures. This failure mode was chosen because of instructor experience with the project and in the automotive industry. During the past 10 years that this type of vehicle project was run while, the most common race day electrical failure was a broken connection between a sensor/motor/actuator and the controller or data collection circuit board, or between the two circuit boards. As part of the project, students learn to make wiring harnesses for connecting electrical subsections of the system. Figure 1 shows a block diagram from a student report with a few clarifications added. There are several connectors used in the system. The computer engineering student’s circuit board connects to a beam break sensor (vehicle speed), the battery (not shown in the figure), the computer (after the race to upload data), and the electrical engineering student’s circuit board. The electrical engineering student’s circuit board connects to the battery (ground return not shown in the figure), the motor, the potentiometer, and the computer engineering student’s circuit board. In total, there are 7 sets of connectors used in the project for the two circuit boards. The electrical engineering students were provided with background information on the FMEA process[3,4] and on safety in automotive electrical systems[5,6] and subsequently performed a rudimentary FMEA to determine the effects of broken connections for their circuit board.

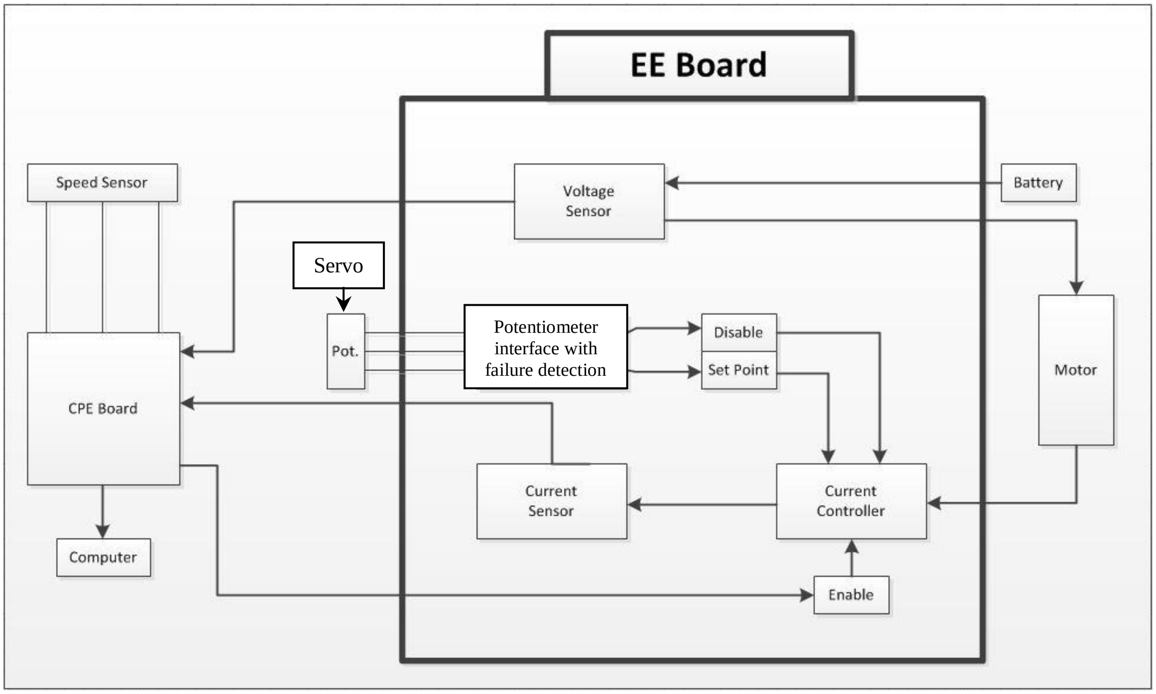

Figure 1: Block Diagram of Electrical System.

After completing the design FMEA process, students learned that there are a several wires that are critical to the vehicle's ability to drive. One of the better student FMEAs is shown in Figure 2. The students, with help from their professor, determined that the enable input and the potentiometer wires have a higher probability of failure due to the small gauge of the wire and the small terminals used in the connections. Students learned that some of the failures effects could be mitigated by adding pull down resistors to force an input state if the wire broke. These inputs were the enable input and the potentiometer wiper input. See Figure A10, in the appendix. The two other potentiometer input wires had much different failure effects if they broke. The positive input to the potentiometer, if broken, would result in the vehicle stopping. The ground wire, on the other hand, if broken, would result in uncontrolled speed of the vehicle. This is similar to the concerns that some Toyota automobiles had a few years ago where an alleged failure in the drive by-wire system caused the cars to drive at full throttle with no means of stopping the car[7]. To mitigate the effects of this failure mode, the students designed an over voltage detection circuit. If the ground wire connection to the potentiometer is broken, the over voltage detection circuit will automatically shut off the motor by pulling the gate of the FET low. While a car that won't move is inconvenient, it is a much safer failure than a car with uncontrolled speed.

Through the FMEA process, students learned the importance of a system-level approach to reliability and safety. The process was a valuable tool for students to see the larger picture of engineering design, beyond that of simply meeting a functional specification. While all of the students implemented the circuit enhancements to mitigate the failure modes, only 50% completed the FMEA tables satisfactorily. It is good that all of the students learned how to implement circuit enhancements to mitigate failure modes, but disappointing that only half of the students completed the FMEA tables. The other half turned in written descriptions of the failure mitigations but did not submit an FMEA table with their final report. The average assessment value was 2.0. In the next offering of the course, in addition to the assigned readings, the professor will spend more time explaining how to fill out and the importance of filling out the FMEA.

Potential Failure Mode and Effects Analysis

Design FMEA

Part Name & Number	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Causes of Failure	OCC	Design Evaluation Technique	DET	RPN	WHEN	WHY	Recommended Actions	Corrective Actions	Area Responsible	SEV	OCC	DET	RPN
Part Function														Action Results			
Motor Positive Wire	open circuit	loss of vehicle propulsion	5	Poor termination	1	check termination	2	10	2	1	make a new cable	make a new cable	student	5	2	1	10
Motor Positive Wire	open circuit	loss of vehicle propulsion	5	Poor strain relief	3	check strain relief	2	30	1	9	reroute cable path	reroute cable path	student	5	1	1	5
Motor Negative Wire	open circuit	loss of vehicle propulsion	5	Poor termination	1	check termination	2	10	2	1	make a new cable	make a new cable	student	5	2	1	10
Motor Negative Wire	open circuit	loss of vehicle propulsion	5	Poor strain relief	3	check strain relief	2	30	1	9	reroute cable path	reroute cable path	student	5	1	1	5
Battery Positive Wire	open circuit	loss of board function & vehicle propulsion	5	Poor termination	1	check termination	2	10	2	1	make a new cable	make a new cable	student	5	2	1	10
Battery Positive Wire	open circuit	loss of board function & vehicle propulsion	5	Poor strain relief	3	check strain relief	2	30	1	9	reroute cable path	reroute cable path	student	5	1	1	5
Battery Negative Wire	open circuit	loss of board function & vehicle propulsion	5	Poor termination	1	check termination	2	10	2	1	make a new cable	make a new cable	student	5	2	1	10
Battery Negative Wire	open circuit	loss of board function & vehicle propulsion	5	Poor strain relief	3	check strain relief	2	30	1	9	reroute cable path	reroute cable path	student	5	1	1	5
Potentiometer Positive Wire	open circuit	loss of vehicle propulsion	5	Poor termination	4	check termination	3	60	2	9	make a new cable	make a new cable	student	5	4	3	60
Potentiometer Wiper Wire	open circuit	floating input no command signal, erratic vehicle speed	5	Poor termination	4	check termination	3	60	2	9	put a pull down resistor on op amp	put a pull down resistor on op amp	student	4	4	3	48
Potentiometer Ground Wire	open circuit	VEHICLE UNCONTROLLED MAX SPEED	5	Poor termination	4	check termination	3	60	2	9	design a failure detection ckt to disable vehicle	design a failure detection ckt to disable vehicle	student	4	4	3	48
Enable Signal Wire	open circuit	erratic on/off behavior of vehicle	5	Porr termination	4	check termination	3	60	2	9	use a pull down resistor to disable vehicle	use a pull down resistor to disable	student	4	4	3	48
Motor Current Data Wire	open circuit	no motor current data recorded or erratic data	2	Porr termination	4	check termination	4	32	2	9	make a new cable	make a new cable	student	4	4	3	48
Battery Voltage Data Wire	open circuit	no battery voltage data recorded or erratic data	2	Porr termination	4	check termination	5	40	2	9	make a new cable	make a new cable	student	4	4	3	48

Figure 2: Wiring Harness FMEA

Summary

This paper presented the electrical engineering students' experiences as part of a team of electrical, computer, and mechanical engineering students who designed, built, and tested a small-scale electric vehicle. The paper gave an overview of the project, described the electrical engineering aspects of the learning objectives, and described Failure Mode and Effects Analysis (FMEA) related to system wiring failures. While students performed exceptionally well in the designing, building, and testing tasks of the project, the FMEA implementation needs improvement. Only half of the students demonstrated that they learned how to fill out an FMEA table. On a positive note, however, all of the students successfully demonstrated understanding of how to enhance circuit designs to mitigate failure modes and increase safety. Along with designing, building, and debugging circuits, the electrical engineering students learned why Failure Mode and Effects Analysis (FMEA) is important and how to design circuits to provide for safer outcomes when wiring connections break and become open.

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Appendix

Detailed Circuit Discussion

Figure A1 shows the triangle wave generator and open-loop pulse width modulation circuits. The “VMotorDrive” signal comes from the output of a Proportional + Integral (P+I) control circuit. As the voltage of the control circuit varies, the duty cycle of the PWM at node 17 will vary. When the current is higher than the desired level, the PWM duty cycle will decrease, thereby lowering the average current consumed by the motor. The duty cycle will increase when the current is lower than the desired level.

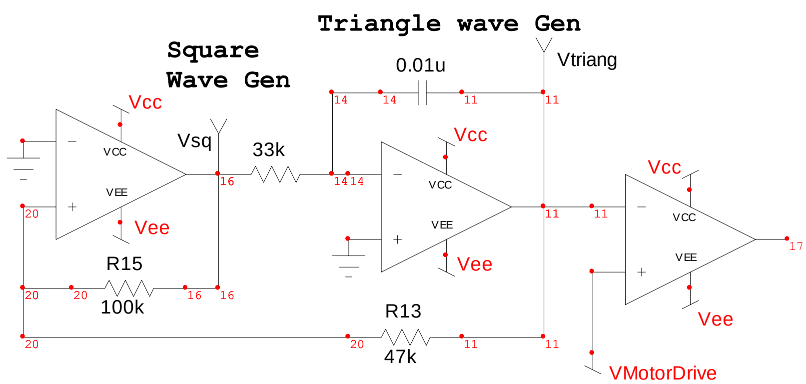


Figure A1: Triangle Wave Generator and open-loop PWM circuits.

It should be noted that Vcc is around 12.8V and Vee is around -9V. Because both of these voltages are unregulated battery voltages, they will vary – generally sagging as the vehicle races. The 9V battery supplying Vee is fairly stable because it does not supply much current. The 12.8V battery, however, will start at well over 13V when fully charged, but will decrease quickly after about 3000mAh is consumed. It should also be noted that the design is bipolar because the difference amplifier, P+I controller, and summing amplifiers were all simpler to implement with positive and negative rails. Because Vcc and Vee are non-symmetric, the oscillator is not balanced. This is not a problem because the closed–loop system compensates for the offset in the triangle wave. Figure A2 depicts the oscillator and a PWM signal from one of the student projects.

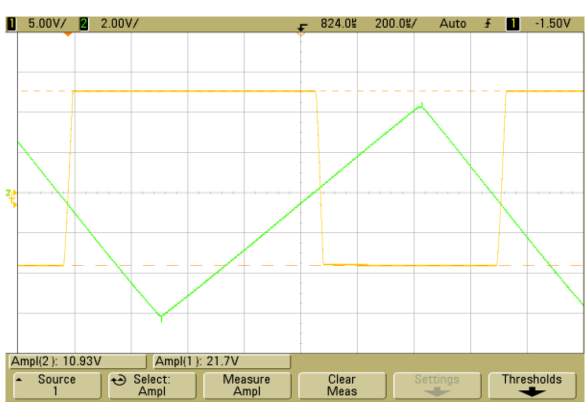


Figure A2: Oscillator output and PWM signal

The current sensing resistor is a 50mΩ 3W wire wound resistor. When an average current of 4A flows through the resistor, 800mW is consumed. While this is not a lot of power, it is wasted. Students learn the trade-off between power consumption and sensor resolution / accuracy. Also, in this circuit design, students learn about ground offset and the error that it causes. Shown in Figure A3 is one of the student's designs for a circuit that converts the voltage from the current sensing resistor into an amplified average voltage that represents the average current flowing through the motor and the FET.

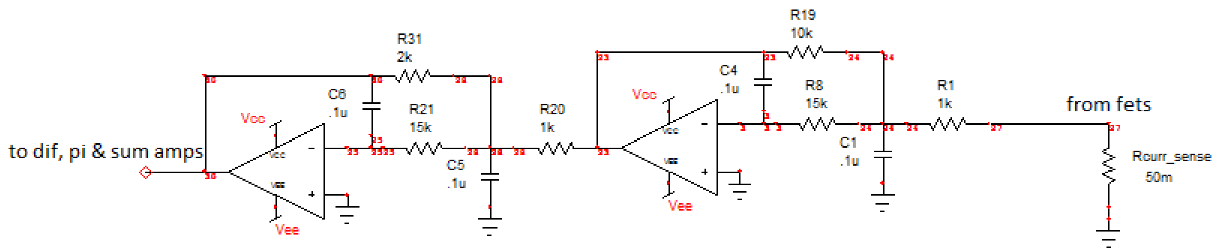


Figure A3: 4^{th} order filter / amplifier.

If there is a ground offset between the ground of the 50mΩ resistor and the op-amps' non-inverting inputs, the voltage at the output of the amplifier will be off significantly. When the students build their circuit boards they learn to keep the high current ground paths separated from the low current grounds. They also learn that the ground path in series with a 50mΩ resistor can have relatively high resistance. They must connect their op-amp grounds as close to the 50mΩ resistor as possible and not further downstream in the high current ground path. Figure A4 shows the results of one of the student's filter design and testing from their final soldered circuit board.

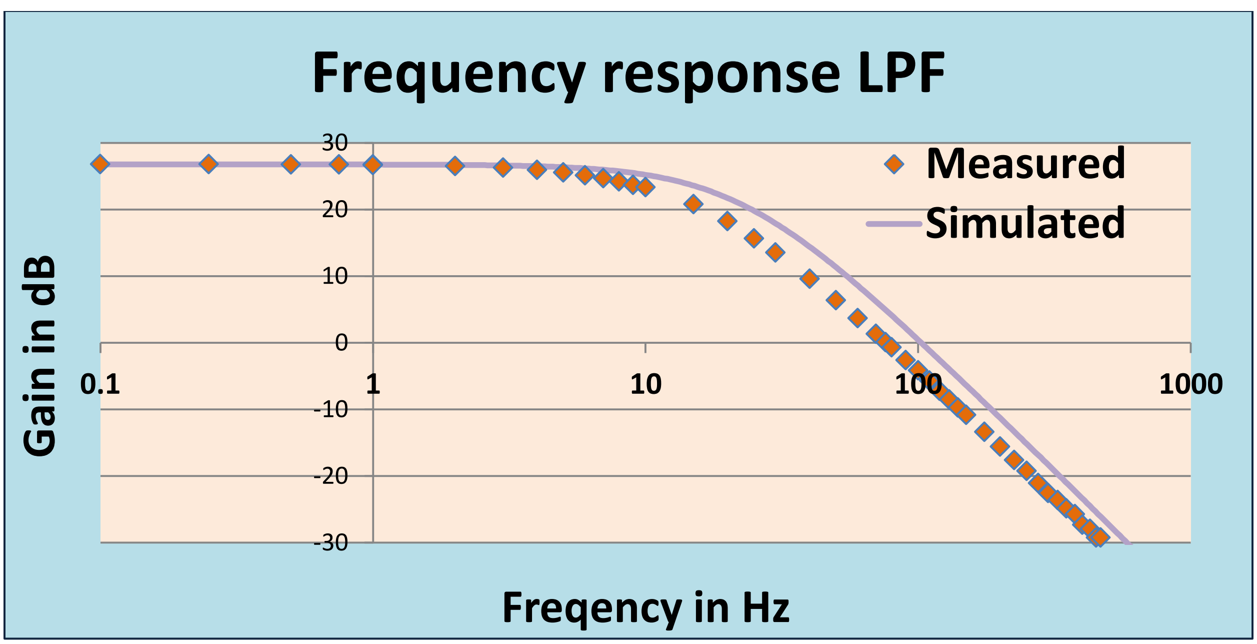


Figure A4: Student example of filter design Bode plot compared with experimental results

The differential amplifier and P+I controller circuit is fairly straight forward for the students to understand. When they build it and test it, however, many challenges arise. Shown in Figure A5 is the circuit.

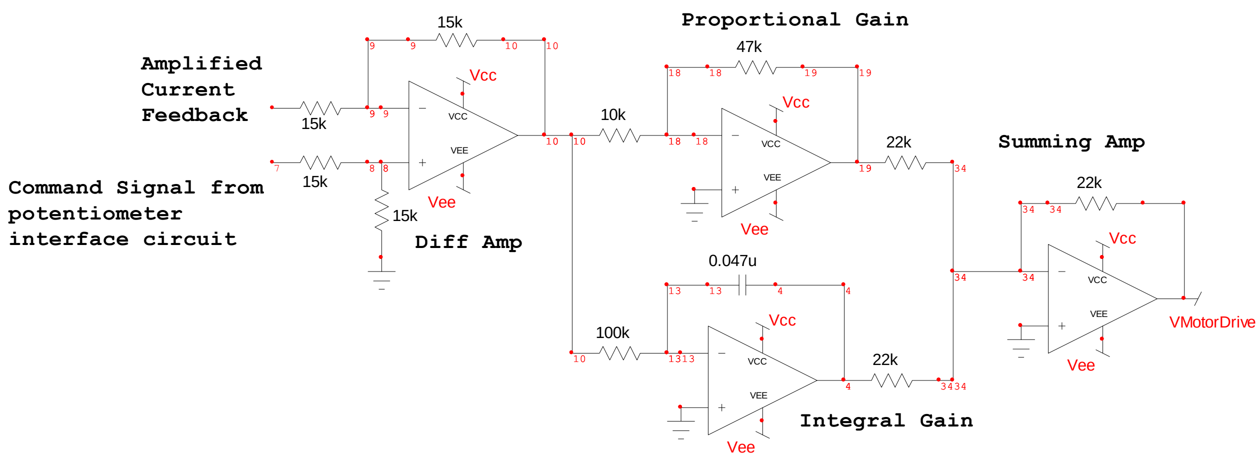


Figure A5: Difference amplifier and P+I controller circuits.

Because there is a delay in the current amplifier / filter circuit, the delay in the integrator needs to be carefully chosen. If the feedback delay and the controller delay are grossly mismatched, the controller will make a terrific oscillator. This typically happens when students don’t measure their component values and put the wrong component in their circuit.   An example of the results of this error is shown in Figure A6. After the students found their mistake, they re-measured the PWM signal and demonstrated the correct circuit behavior – shown in Figure A7.

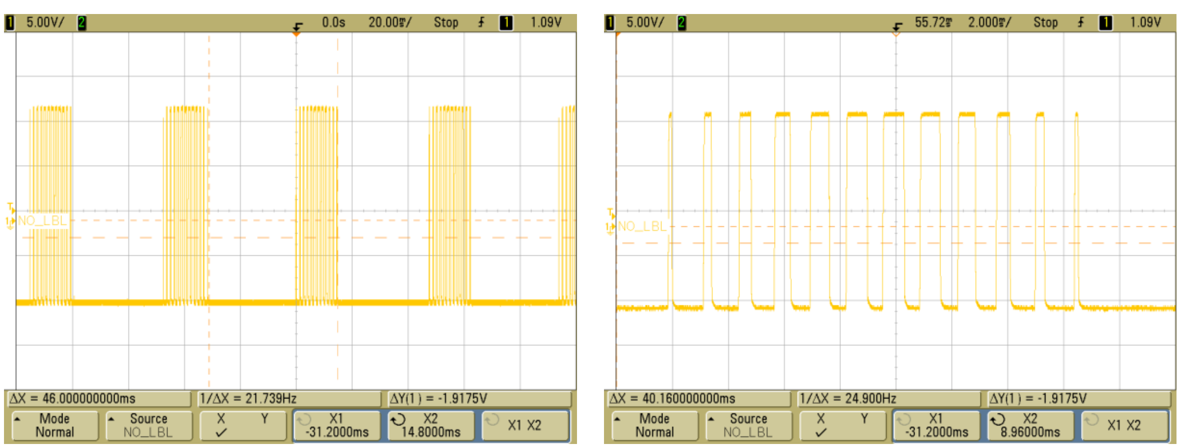


Figure A6: Controller Oscillation due to feedback delay. The oscilloscope screen capture on the right shows one of the sets of pulses. It shows the result of the integrator – turning the FET on and back off as the controller output rises and falls through the triangle wave controlling the PWM duty cycle.

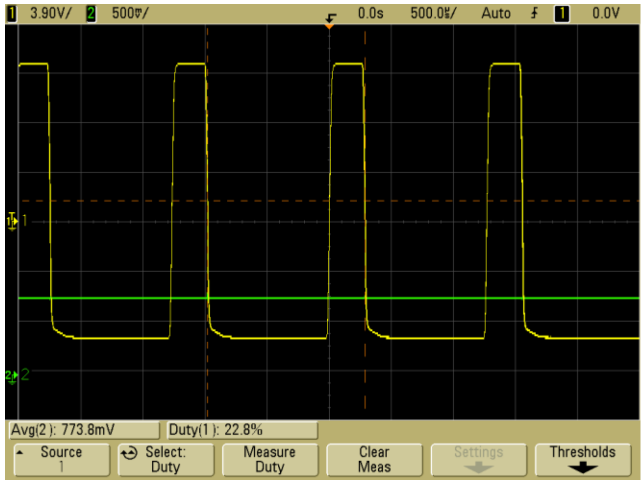
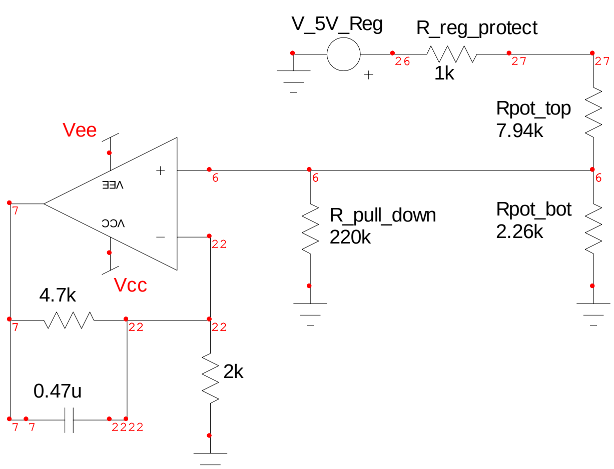


Figure A7: Controller Oscillation corrected after incorrect circuit components were replaced and excessive feedback delay illuminated. Figure shows a stable PWM signal.

The potentiometer interface circuit is a straight forward circuit. Most of the students designed a circuit similar to the example shown here. In this example, a five volt regulator supplies the high side of a potentiometer that is grounded on the other end. The wiper is connected to a non-inverting amplifier with a gain designed such that the output voltage of the amplifier matches the voltage equivalent of 4A average current flowing through the motor. The circuit is shown in Figure A8. There are two resistors in the circuit that are used to prevent negative consequences from connection failures. Rpull_down forces the input low if the wiper wire breaks and R_reg_protect limits the current sourced by the voltage regulator if the high side wire of the pot shorts to ground (node 27).



This pot is off the board. The 2.26k varies from 0 to ~2.6k. It must be measured on the vehicle when the servo turns

Figure A8: Potentiometer interface circuit.

The FET and Flyback diode circuit, shown in Figure A9, is also straight forward and easy for the students to understand. Students learn about the need for the flyback diode when they measure the inductive spike from the motor when the flyback diode is not in the circuit. With the diode in the circuit, they measure the ringing when the FET turns off. To add a margin of safety, three FETS are used in parallel. Students calculate the average power dissipated in the FETS by measuring the signals: source to ground and drain to ground. From the voltage across the sense resistor, they infer the current and calculate the power. The LM324 slew rate limits and the gate resistor slows the switching even more. Rgate is necessary for allowing enable and failure detection circuits to turn off the FET without damaging the op-amp.

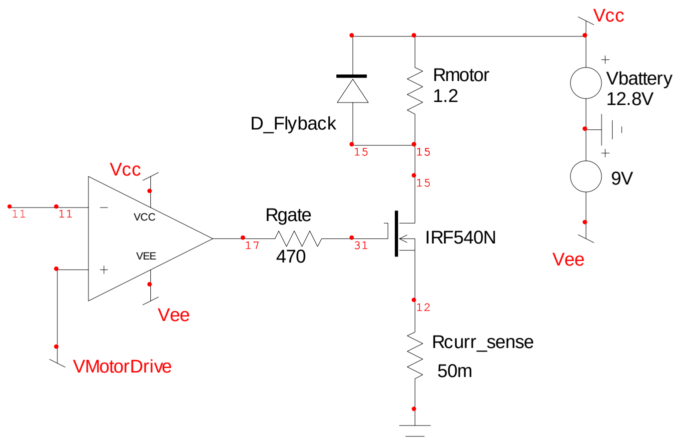


Figure A9: PWM driver, FET, Flyback diode, and current sensing resistor circuit.

Appendix

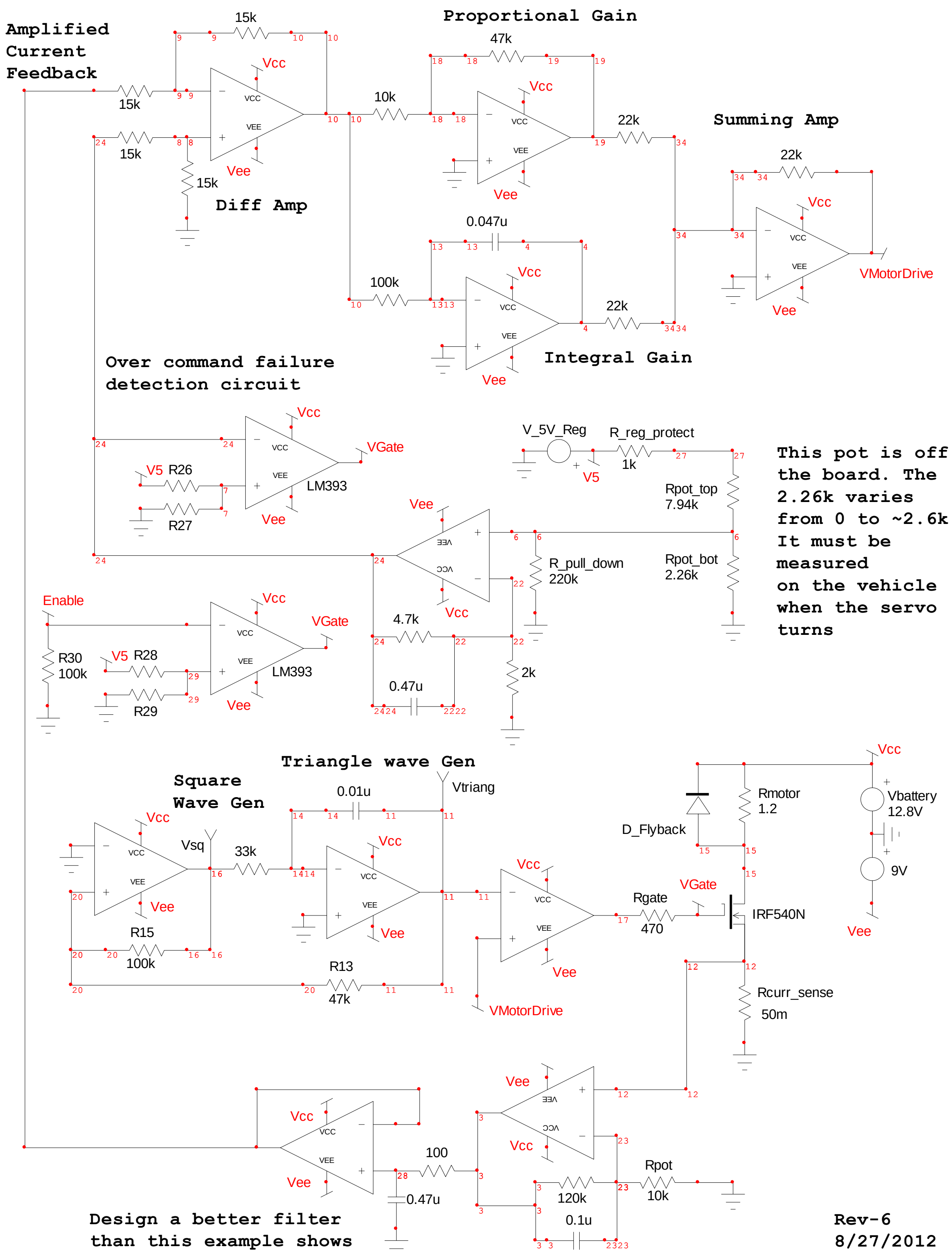


Figure A10: Circuit Diagram representative of the electrical engineering student circuit boards.