Hydro-Gear Multi-Motor Control System Final Project Report

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1. Project Design Introduction

1.1. Motivation

The Multi-Motor Control System project sponsored by Hydro-gear consists of developing a control system able to drive six brushed DC motors coupled to a gearbox as a low cost alternative to using a single AC motor in the production of electric zero turn riding lawn mowers. Functionality will be replicated with the use of an embedded system, PWM circuitry, and circuit simulation software.

1.2. Background and Objectives

Multiple motors, when linked to a common drive shaft, can produce the same torque as a single larger motor at a fraction of the cost. This creates an opportunity to decrease the total cost of systems which use motors of this variety, thus making them more attractive options for potential customers. This attraction can be increased more with promises of future repair savings by allowing each of the smaller motors to be independently diagnosable and exchangeable.

The objectives of this project are:

1. To use multiple smaller DC motors in parallel to produce torque similar to current motors.
2. Employ a feedback system to help ensure the component motors operate together at an intended amperage, extending their lifespan.
3. Be compatible with a specified zero-turn mower.
4. Provide mechanical output comparable with the current motor in the mower.

2. System Requirements

This system will use six 12v DC motors, powered by pulse width modulation circuitry and other control hardware capable of receiving variable electrical input signals from various sensors. Signals are provided by potentiometers already attached to the control arms of the zero-turn mower, and various thresholds of input voltage will correspond to various types of desired mechanical output from the multi-motor. The system will also receive inputs from other sensors needed to diagnose equipment faults.

The system **SHALL** propel a zero turn riding lawn mower for up to 2 hours
The system **SHALL** be able to operate six 12V DC brushed motors.
The system **SHALL** be able to interface with pre-existing components on the mower.
The system **SHALL** maximize efficiency when supplying current to the motors.
The system **SHALL NOT** lose more than 10% of its speed on inclines.

2.1 Cross Reference Verification Matrix

Req #	Requirement	Allocation Level	Verification Type
1.	The system **SHALL** propel a zero turn riding lawn mower for up to 2 hours.	System Level	Analysis
2.	The system **SHALL** be able to operate six 12V DC brushed motors.	System Level	Demonstration
3.	The system **SHALL** be able to interface with pre-existing components on the mower.	System Level	Analysis
4.	The system **SHALL** maximize efficiency when supplying current to the motors.	System Level	Demonstration
5.	The system **SHALL NOT** lose more than 10% of its speed on inclines.	System Level	Analysis
6.	The physical subsystem **SHALL** provide power to all other subsystems.	Physical Subsystem	Demonstration
7.	The physical subsystem **SHALL** have a safety button.	Physical Subsystem	Demonstration
8.	The physical subsystem **SHALL** have a light panel.	Physical Subsystem	Demonstration (Future Team)
9.	The physical subsystem **SHALL** prevent the reverse polarity of batteries.	Physical Subsystem	Demonstration/ Analysis

10.	The physical subsystem **SHALL** not work if there is no weight on the seat.	Physical Subsystem	Analysis
11.	The physical subsystem **SHOULD** output error notifications in case of component malfunctions.	Physical Subsystem	Demonstration
12.	The sensor subsystem **SHALL** provide information to all other subsystems.	Sensor Subsystem	Demonstration
13.	The sensor subsystem **SHALL** utilize throttle potentiometers to provide the control system voltage values based on the positional input for speed control.	Sensor Subsystem	Demonstration
14.	The sensor subsystem **SHALL** receive input from the SNDH-T series encoders/sensor to determine if the motors are functioning properly.	Sensor Subsystem	Demonstration
15.	The sensor subsystem **SHALL** obtain internal motor temperature values from a thermal sensor to send to the control subsystem.	Sensor Subsystem	Demonstration
16.	The sensor subsystem **SHALL** monitor the presence of the user via the operator presence control.	Sensor Subsystem	Analysis
17.	The sensor subsystem **SHALL** obtain information from the emergency kill switch.	Sensor Subsystem	Analysis
18.	The output subsystem **SHALL** receive input from the motor control system.	Output Subsystem	Demonstration

19.	The output subsystem **SHALL** provide feedback.	Output Subsystem	Demonstration
20.	The output subsystem **SHALL** cease operation if there is no user.	Output Subsystem	Demonstration
21.	The output subsystem **SHOULD** not operate when the battery is installed correctly.	Output Subsystem	Demonstration/ Analysis
22.	The output subsystem **SHOULD** cease operation if the safety button is pressed.	Output Subsystem	Demonstration
23.	The control subsystem **SHALL** accept input signals from required sensors.	Control Subsystem	Demonstration
24.	The control subsystem **SHALL** provide appropriate motor signals to output subsystem.	Control Subsystem	Demonstration
25.	The control subsystem **SHALL** monitor the status of safety switches.	Control Subsystem	Analysis
26.	The control subsystem **SHALL** operate off battery power from mower batteries.	Control Subsystem	Demonstration
27.	The control subsystem **SHOULD** output signals to L.E.D. to notify users of change in status.	Control Subsystem	Demonstration (Future Team)

Table 1: Cross Reference Verification Matrix

3. System Architecture

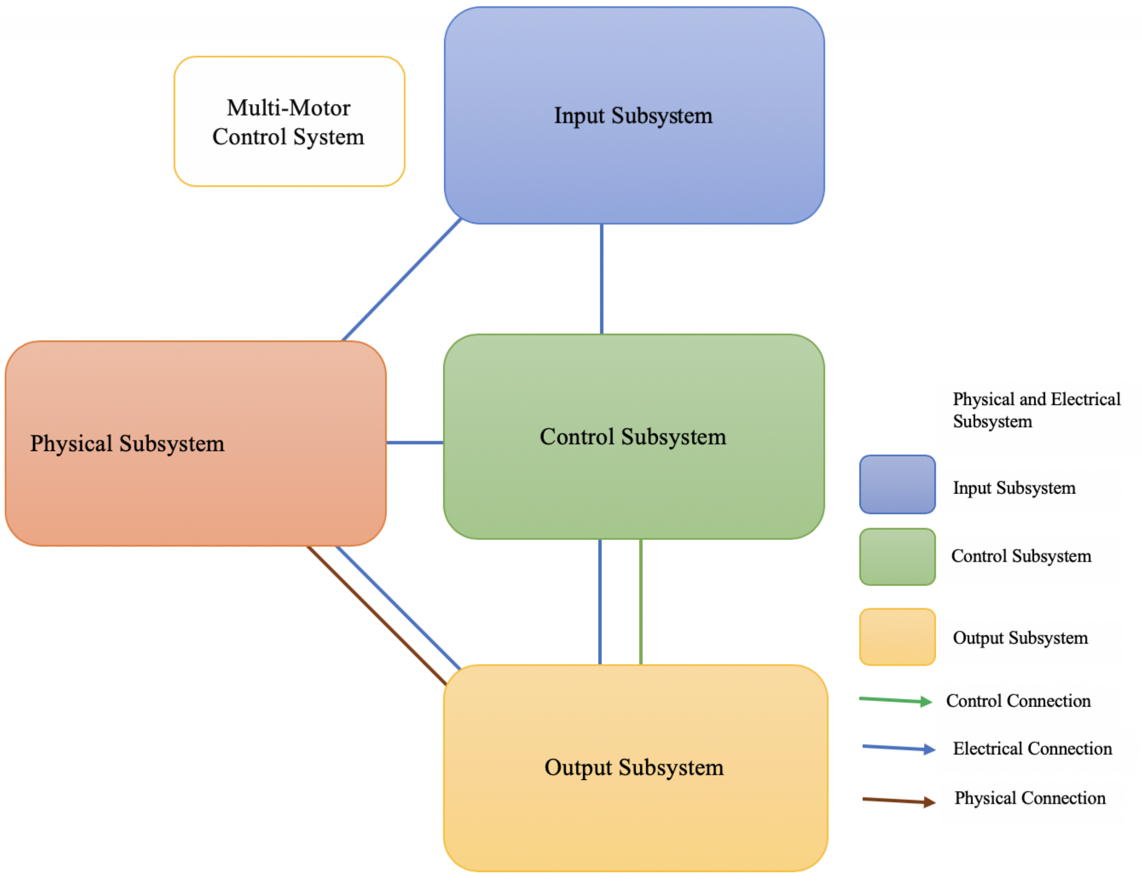

Figure 1: Full System Block Diagram

4.System Design Choices

4.1. Physical Subsystem Design Choices

For the safety subsystem many safety components and circuit designs were evaluated to prevent the reverse polarity of batteries. The options were narrowed down to three different protection component archetypes. The three were diode protection, P-channel MOSFET protection, and N-channel MOSFET protection. A PUGH Matrix was used to compare each type of protection, and N-channel MOSFET was chosen as the best option for the safety subsystem. The N-channel has the least power losses, the lowest voltage drop, and the highest efficiency.

4.2. Sensor Subsystem Design Choices

To select sensors that more closely fulfill the requirements, two PUGH Matrices were utilized to compare different candidates for the encoder and thermal sensors. For the encoder, the SNDH-T Series sensors and the SD101201 sensor were compared. As shown by the PUGH Matrix, although SNDH-T was more expensive, it more closely coupled with the current chassis elements, and thus it was selected.

For the thermal, the LM35 temperature sensor, the DS18B20 temperature sensor, and the LM75 temperature sensor were compared. The more basic LM35 was shown in the PUGH Matrix to satisfy or exceed the most amount of requirements while maintaining a low cost, and so it was selected as the option for the thermal sensor.

4.3. Output Subsystem Design Choices

After considering several options for the PWM source, a PUGH Matrix has been constructed to compare two possible options, one of which is the Sabertooth motor drive, and the other is a self-built PWM source circuitry using an h-bridge gate IC. While both sources have met our requirement conditions the PUGH Matrix showed that building a PWM source is the best option for the design. It provided the current level needed for the motors to achieve the desired output, as well as begin the most cost effective option.

4.4. Control Subsystem Design Choices

The selection of the embedded system that will be used in the control subsection was decided using a Pugh Matrix based on the factors of serial communication, I/O inputs, and cost. The two products compared were the STM32 “Blue Pill” and the Arduino nano. Both choices met the requirements to reach project completion, but the incredibly low price and versibility of the STM32 board proved more useful. The STM32 provides room to grow with designs and multiple USART pins for packetized serial communications. Due to the large number of I/O pins required initial testing was done using a larger Arduino Mega board until signals are able to be propagated to all motor drive circuits. The STM32 will be used in the final prototype.

5.Physical Subsystem

The physical subsystem consists of the major mechanical systems, the main chassis, gearbox, control box, battery, and safety circuitry. The safety circuitry prevents the overload and the reverse polarity of batteries.

5.1. Physical Requirements

The physical subsystem **SHALL** provide power to all other subsystems.

The physical subsystem **SHALL** have a safety button.

The physical subsystem **SHALL** have a light panel.

The physical subsystem **SHALL** prevent the reverse polarity of batteries.

The physical subsystem **SHALL** not work if there is no weight on the seat.

The physical subsystem **SHOULD** output error notifications in case of component malfunctions.

5.2. Physical Architecture

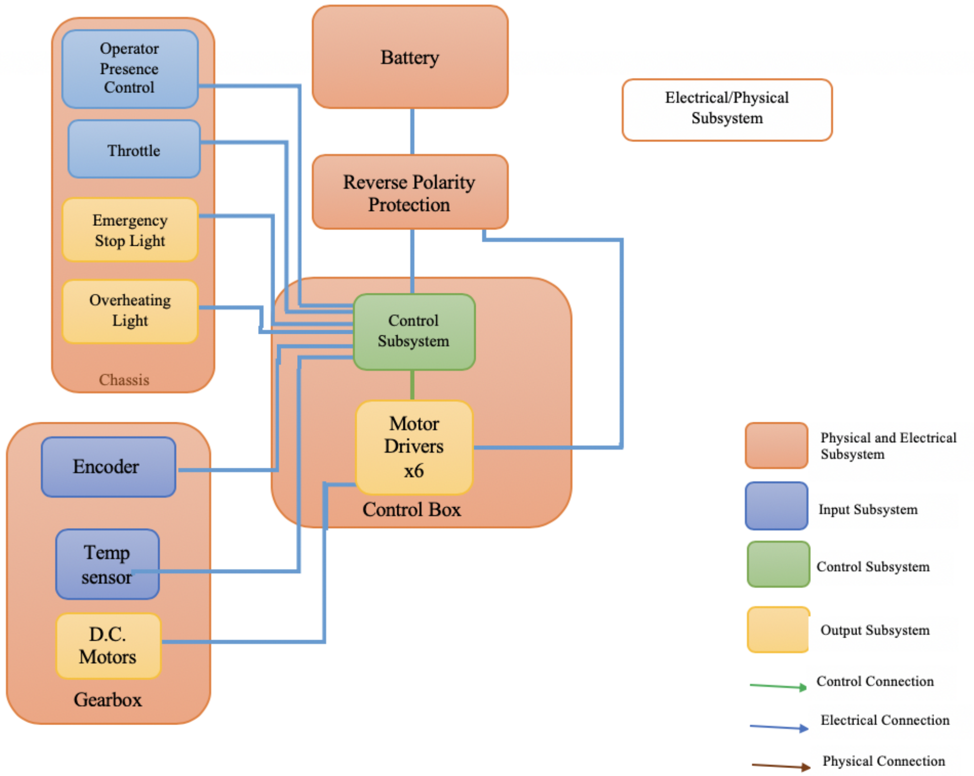

Figure 2: Physical System Block Diagram

The physical subsystem consists of the main chassis, gearbox, control box, battery, and reverse polarity protection. The main chassis houses the operator presence control, throttle, emergency stop light, and overheating light, these are electrically connected to the control subsystem. The gearbox interfaces with the encoder, temperature sensor, and DC motor which is connected to six motor drivers.

5.3. Physical Design Challenges

Within this subsystem, the largest challenge faced was designing the reverse polarity protection. By changing the batteries of the system, the batteries need to be reconnected. In this situation, it is possible that the polarity of the battery could be applied in the reverse direction. The diode, P-channel MOSFET, and N-channel MOSFET would be considered to build the reverse polarity protection circuit. The cost, size, power loss, voltage drop, and efficiency of the component would be considered when designing the circuit.

5.4. Physical Design Options

Within the physical subsystem, reverse polarity protection of the batteries will be discussed. There are three different choices for reverse battery protection: diode, P-channel MOSFET, and N-channel MOSFET. The advantages of the diode protection model are simplicity and cost. The disadvantages of the diode protection model are larger power losses and a substantial voltage drop. MOSFET protective circuitry is a better alternative to the diode protection model because of a lower voltage drop and lower power losses. The disadvantage of MOSFET (metal-oxide semiconductor field-effect transistor) protection is the cost of MOSFETs are more expensive than diodes. The n-channel MOSFET protection offers the highest efficiency, especially in high power.

P3: N-Channel MOSFET Protecttion
P2: P-Channel MOSFET Protection
P1: Diode protection

Criteria	C	P1	P2	P3
cost	C1	S	-	+
size	C2	S	-	+
Power loss	C3	-	+	S
Voltage Drop	C4	-	+	S
Efficiency	C5	-	+	S
	Σ +	0	3	2
	Σ S	2	0	3
	Σ −	3	2	0

Table 2: PUGH Matrix for safety subsystem

5.5. Physical Summary

Based on PUGH Matrix evaluation of criteria regarding cost, size, power loss, voltage drop, and efficiency, it is recommended that the physical subsystem uses the N-channel MOSFET to build the safety subsystem. The N-channel MOSFET has lower power losses and the highest efficiency. Thus, it is sufficient for our physical subsystem.

6.Sensor Subsystem

The sensor subsystem interfaces with the control subsystem to provide input data to be processed by a microcontroller. To accomplish this, all of our sensory components will connect to our control subsystem via a single system bus. Each input will go through one of six components to process user input data that will be sent to the control subsystem to obtain the desired output. The six sensory components of this subsystem are: a thermal sensor, SNDH-T series encoder, emergency kill switch, throttle potentiometers, ignition , and operator presence control. The thermal sensor and SNDH-T series encoder are the two main sensors that will need to be incorporated in the sensor subsystem design. The other sensors are either already provided or are relatively simple implementations.

6.1. Sensor Requirements

The sensor subsystem **SHALL** provide information to all other subsystems.
The sensor subsystem **SHALL** utilize throttle potentiometers to provide the control system voltage values based on the positional input for speed control.
The sensor subsystem **SHALL** receive input from the SNDH-T series encoders/sensor to determine if the motors are functioning properly.
The sensor subsystem **SHALL** obtain internal motor temperature values from a thermal sensor to send to the control subsystem.

The sensor subsystem **SHALL** monitor the presence of the user via the operator presence control.

The sensor subsystem **SHALL** obtain information from the emergency kill switch.

6.2. Sensor Architecture

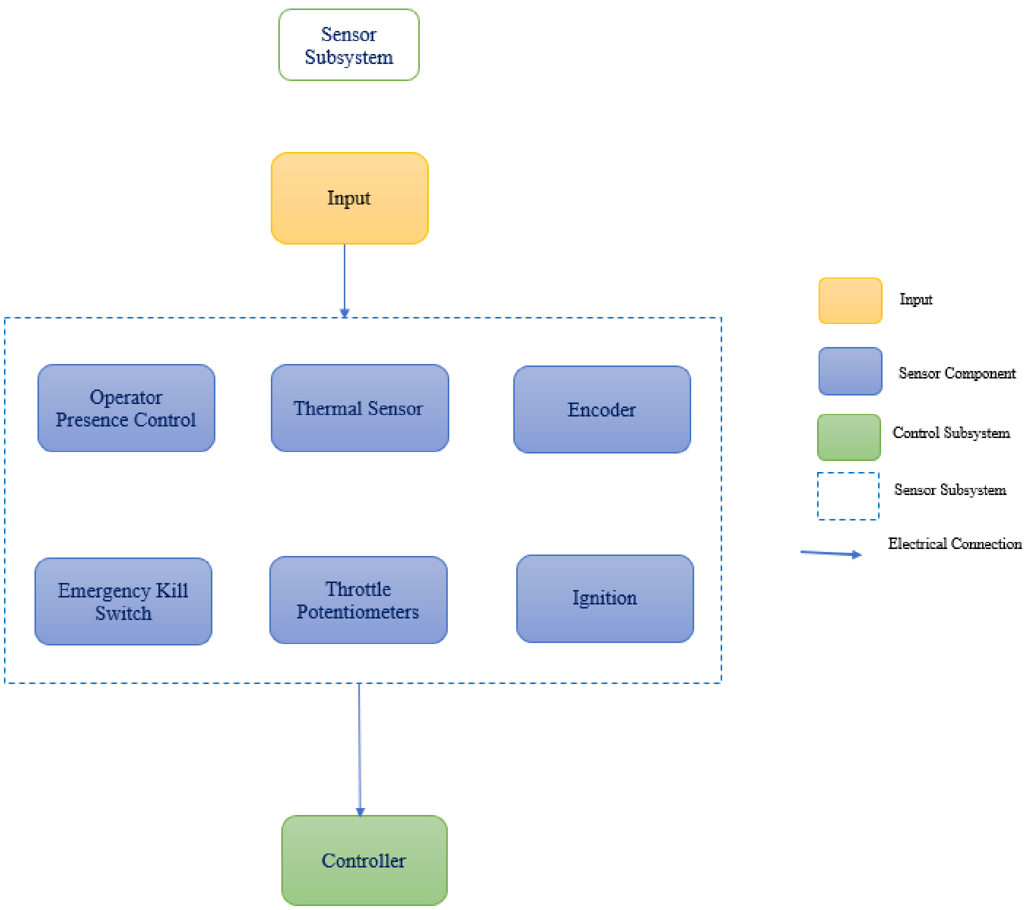

Figure 3: Sensor System Block Diagram

6.3. Sensor Design Challenges

The biggest challenge presented when designing the sensor subsystem was how to gather all the information from each sensor component and compile it into useful data for our control subsystem. Each individual sensor component also has design challenges associated with them, but as a whole this is the most pressing issue. To make the sensor subsystem effective each sensor component must be able to communicate with a central control system, like a STM32. Thus, all the sensors that are selected must be able to interface with this specific control system. This will allow the system to compile a flux of input information from multiple sources. Although, this can lead to more efficient sensor options potentially being void due to it not being compatible with the control system. These constraints could limit design options, potentially increasing the cost of production and making sensors that are already in use by the company obsolete. With the limitations addressed and the main challenges laid out, here are the metrics that were used when selecting sensors that met the minimum requirements for the project:

Compatibility with Selected Control Subsystem: All six sensors must be able to communicate with the selected control subsystem. The flow and compilation of input information is crucial to obtain the necessary outputs that are desired.

Cost: Maximizing efficiency while minimizing cost is vital when making a purchasing decision. When choosing a sensor for this subsystem the mentality is no different. Most of these sensors are inexpensive, but it is still essential that they function properly while still being under budget.

Installation/Implementation: Each sensor will have an inherent size and weight. This needs to be accounted for when making a selection.The housing component already exists for this Multi-Motor Control system. Thus, to maximize efficiency, the chosen sensor comment should be able to rest comfortably within the already existing housing compartment. This will alleviate the need to adjust the already existing components and compartments making it easier to manufacture.

Ease of Replaceability: Each sensor should be as easy to replace as possible. This is not as important as the former metrics, but will make it more consumer friendly and easier to fix.

Functionally Dependent: Most of these sensors will be under harsh environments and will need to maintain functional integrity when exposed to various elements. Some of these conditions include: extreme heat, frictional wear and tear, dirt and debris, etc. The selected sensors need to survive and thrive in these particular conditions to ensure longevity of the system.

6.4. Sensor Design Options

6.4.1 Encoder Sensor

The design options considered for the encoder sensor were the SNDH-T Series sensors and the SD101201 sensor. The SNDH-T Series consists of a family of quadrature sensors with varying connector fixtures but the same internal systems. Which specific model of the four to be used would be decided as further specifics regarding the physical connections between the sensor subsystems and the control subsystems are finalized. Both options are hall effect sensors with flange mounted iron gear sets, which are used to measure the speed and direction of a rotating axle. One noted difference between the two is the target size of the measured rotating axle, with the SNDH-T having a target size of 0.2” and the SD101201 having a target size of 0.25”.

A PUGH Matrix below compares the two, using the metrics of having a compatible recommended operating temperature, target axle thickness, reverse voltage protection, a compatible operating voltages, and cost. The PUGH Matrix shows the SNDH-T Series to be the superior option, as though more expensive, its target axle thickness fits better with the current chassis.

P2: SD101201

P1: SNDH-T

Criteria	C	P1	P2
Operating Temperature	C1	+	+
Target Axle Thickness	C2	S	-
Reverse Voltage Protection	C3	S	S
Operating Voltage	C4	S	+
Cost	C5	-	S
	S +	1	2
	S S	3	2
	S -	1	1

Table3: PUGH Matrix for encoder sensor

6.4.2 Temperature Sensor

The options considered for the temperature sensor were the LM35 temperature sensor, the DS18B20 temperature sensor, and the LM75 temperature sensor. These were considered due to the ease with which their outputs pair with the proposed control system hardware and their operating temperature.

To compare the three options, the metrics of operating temperature, compatibility with the control system, power supply range, reading accuracy, and cost are considered by the PUGH Matrix for the temperature sensor below. As demonstrated by the PUGH Matrix, the LM35 meets the requirements of the temperature sensor while being operable within the prefered power supply range and while maintaining a low cost.

P3: DS18B20
P2: LM75
P1: LM35

Criteria	C	P1	P2	P3
Operating Temperature	C1	+	S	S
System Compatibility	C2	S	S	S
Power Supply Range	C3	S	-	-
Accuracy	C4	S	+	+
Cost	C5	S	-	-
	S +	1	1	1
	S S	4	2	2
	S -	0	2	2

Table4: PUGH Matrix for temperature sensor

6.5. Sensor Summary

Based on the requirements for the sensor subsystem elements and the comparisons of the two PUGH Matrices, the SNDH-T Series hall sensor and the LM35 temperature sensor are the recommended components to fill the Encoder Sensor and Thermal Sensor roles, respectively. The SNDH-T hall sensor most aptly meets the target requirements for the encoder sensor and though it is the more expensive option, it is more compatible with the current chassis. For the thermal sensor the LM35 provides all the required functionality while maintaining a low cost.

7. Output Subsystem

The output subsystem contains both the mechanical output provided by the 12v motors when current is applied as well as the hardware and lights that warn of overheating or deteriorating.

7.1. Output Requirements

The output subsystem **SHALL** receive input from the motor control system.

The output subsystem **SHALL** provide feedback.

The output subsystem **SHALL** cease operation if there is no user.

The output subsystem **SHOULD** not operate when the battery is installed correctly.

The output subsystem **SHOULD** cease operation if the safety button is pressed.

7.2. Output Architecture

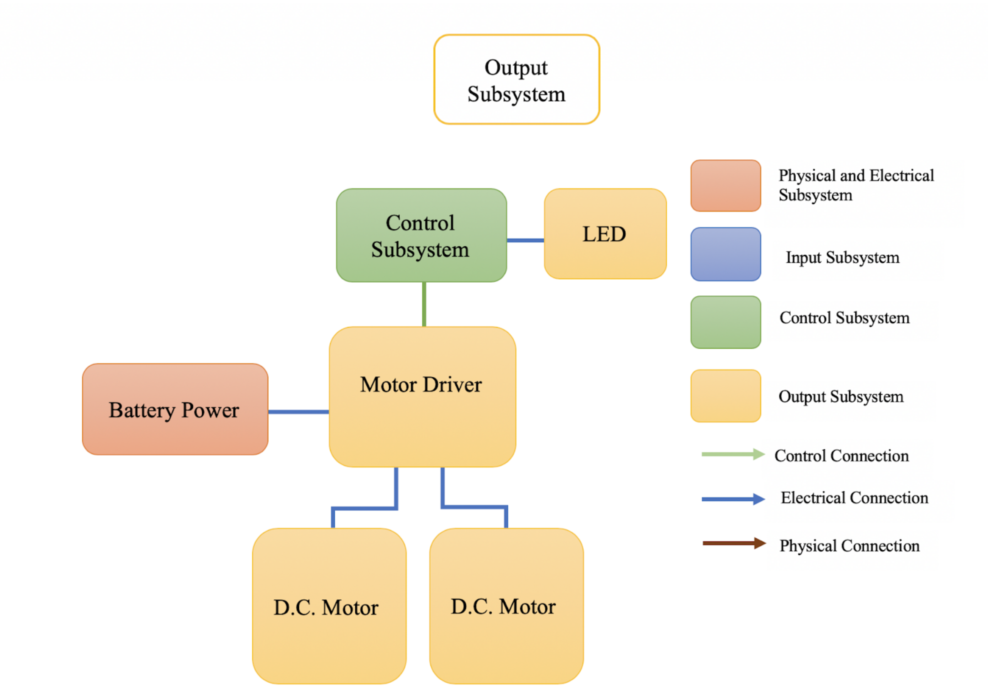

Figure 4:Output System Block Diagram

7.3. Output Design Challenges

The design challenge that has been considered for the design option is the Pulse Width Modulation (PWM) circuitry for the connected motors. The challenge was choosing between the following two options, the first was the Sabertooth motor drive and the second option was to build a PWM source using h-bridge gate driver IC. First it was decided to use the Sabertooth motor driver seeing that it already had a 32kHz ultrasonic switching frequency, however, it was evident that it is not enough to power the motors for the duration and the conditions that its required. Also, the Sabertooth motor drive costs around $125 which is very pricey considering the alternative. Therefore, building a PWM circuitry would be the best option. Building a PWM circuitry means that it would be possible to provide up to 100A current to each motor safely. After doing some research, the h-bridge was chosen as the better option seeing that it has 2 half bridges which will lower the amount of IC used in the design, also, it can source or sink as high as 1A peak current pulses which will be able to provide the high PWM frequency that is required. Not only does it exceed the necessary level of currents but also it is a better option cost wise.

7.4. Output Design Options

The design options considered were the Sabertooth motor drive and a self-built PWM circuitry using an h-bridge gate driver IC. Both options are compatible with our requirements. However, for a better design choice the two have been compared using a PUGH Matrix. The PUGH Matrix compares the cost, safety, size, easy implementation, and functionality. There are not many differences between the two options in regards to safety however, they differ in cost, size, implementation, and functionality. Based on the PUGH Matrix (*table 5*), using the self-built PWM circuitry would be the better option seeing that it is more likely to provide the needed output for the design since it has better cost, and functionality.

P2: Sabertooth Motor Driver

P1: Self-Built PWM Circuitry

Criteria	C	P1	P2
Inexpensive to Operate	C1	S	-
Easy to Implement	C2	-	S
Functionality	C3	S	-
Safe to Operate	C4	S	S
Space Occupancy	C5	-	+
	Σ +	0	1
	Σ S	3	2
	Σ −	2	2

Table 5: PUGH Matrix comparing two PWM sources.

7.5. Output Summary

Based on the output requirements and the results from the PUGH Matrix it is evident that the better choice is the self-built PWM circuitry using the h-bridge gate IC. The self-built circuit is not only the cheaper option but also it can provide the current levels needed to meet the desired outputs.

8. Control Subsystem

Due to the number of parameters monitored by sensors, an embedded systems platform was chosen for the project's control subsystem. This platform will interface with all other subsystems and promulgate signals throughout the Multi-Motor control system.

8.1. Control Requirements

The control subsystem **SHALL** accept input signals from required sensors.

The control subsystem **SHALL** provide appropriate motor signals to output subsystem.

The control subsystem **SHALL** monitor the status of safety switches.

The control subsystem **SHALL** operate off battery power from mower batteries.

The control subsystem **SHOULD** output signals to L.E.D. to notify users of change in status.

8.2. Control Architecture

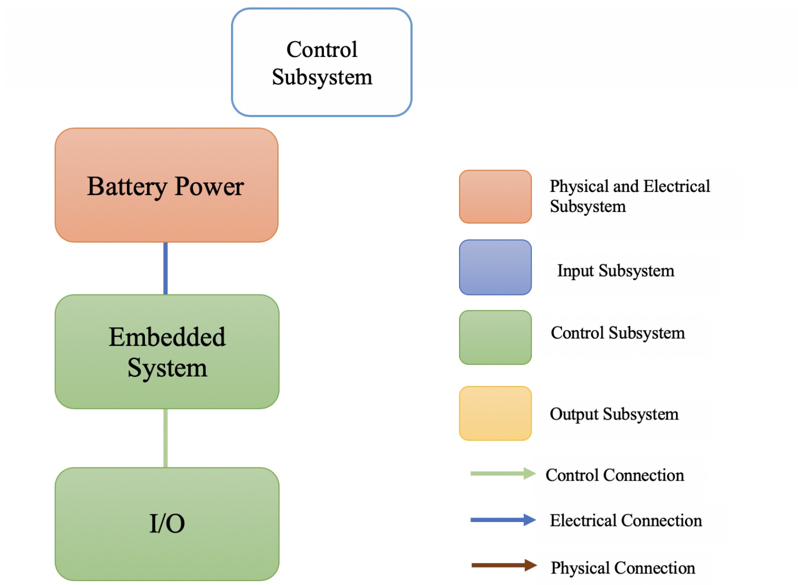

Figure 5: Control System Block Diagram

Figure 6 shows a block diagram for the control system. It will be wired into battery power and will require some safety circuitry to assure correct voltage levels are maintained throughout use. Data will be processed by the embedded system and distributed to all other subsystems through the I/O interface.

8.3. Control Design Challenges

The control system will be taking input signals and providing proper output signals to deliver PWM signals to the motor drivers, therefore an embedded control system is required to efficiently receive and send information to and from the other subsystems. Another challenge to take into consideration is the number of sensors currently being used on the mower system. Having an embedded system with a sufficient number of inputs and outputs will allow the sensor subsystem to efficiently distribute data throughout the Multi-motor Control system.

8.4. Control Design Options

The design options considered for this section are the STM32 “Blue Pill” and the Arduino nano control boards. The STM32 chip is by far the cheapest and simplest option. This board offers 3 USART (Universal Synchronous/Asynchronous Receiver/Transmitter) channels, 37 I/O pins, and 72MHz CPU speed

The “Blue Pill” is somewhat user friendly and has a list price under $3.00. The board has the processing power required for this project, but has a few flaws. The board has an infamously weak 3.3 voltage regulator on the board which makes it unreliable when powering any level of sensors. The board also does not include a usb chip which requires an external SWD programmer to use it.

The next option is the Arduino nano, This is a mid level board that is slightly more user friendly than the STM32 board, but with a much higher purchase price. At $22.00 the arduino comes with 1 USART channel,14 I/O pins, and a CPU speed of 16MHz. This board makes up for the negative aspects of the STM32 with a usb port and a more stable voltage regulator allowing more sensors to be powered. A pugh matrix was used to choose the best option for an embedded system.

P2: Arduino nano

P1: STM32 "Blue Pill"

Criteria	C	P1	P2
Cost	**C1**	+	**S**
Ease of use	**C2**	**S**	+
I/O pins	**C3**	+	**S**
USART ports	**C4**	+	**S**
Clock Speed	**C5**	+	**S**
	Σ +	4	1
	Σ **S**	1	4
	Σ –	0	0

Table6: PUGH Matrix comparing control options

8.5. Control Summary

Based on design requirements and the result of the control Pugh matrix the STM32 board is the most economical and ideal choice to complete the design. Even though the board will require external hardware to bootload and is not breadboard compatible, the low cost and high functionality will be sufficient for the completion of the Multi-Motor Control system. Due to the high number of outputs required to supply PWM signals to 6 motor drivers, a larger arduino board will be used to test PWM circuitry and write the main structure of the embedded system until Motor drive circuitry is finished.

9. Design Details

9.1. Safety Circuitry

The N-channel MOSFETs would be considered to build the reverse polarity protection circuit. N-channel MOSFETs are ideal for providing reverse current protection with minimal loss. When the battery is installed properly, it shorts the diode. When the battery is installed incorrectly, it opens the diode.

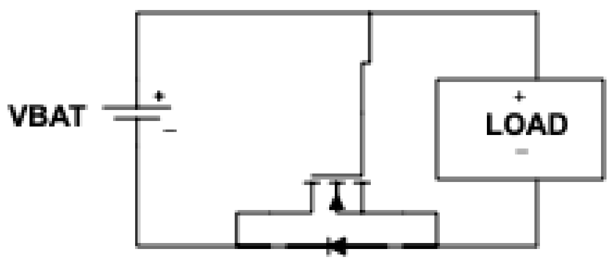

Figure 6: Reverse Polarity Protection Circuit Design

The voltage regulator would be considered to build the overload protection circuit. The purpose of a voltage regulator is to keep the voltage close to a desired voltage. A voltage regulator used if the power supply produces a voltage greater than what components on the circuit required.

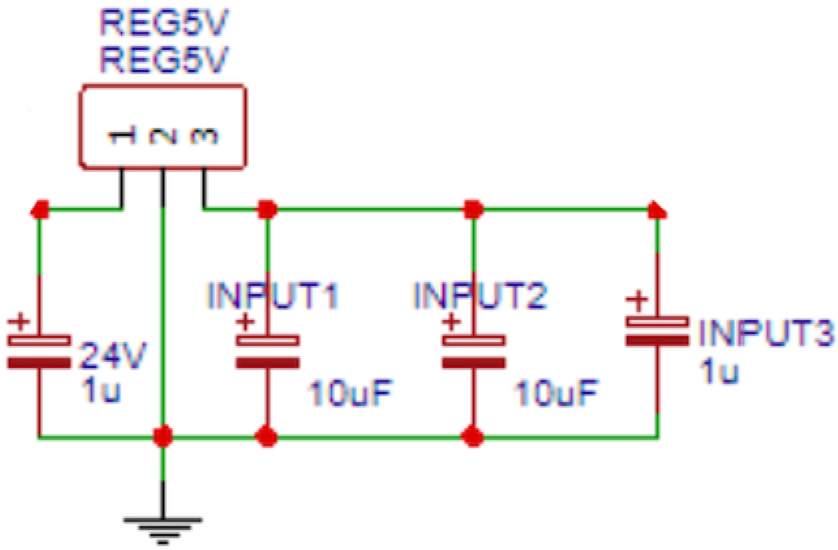

Figure 7: Voltage Regulator Circuit for Overload Protection Circuit Design

9.2. Potentiometer Circuit

Potentiometer is a three wire resistive device that acts as the voltage divider with a shaft to control for setting the division ratio. In this design, the potentiometer outputs the voltage value from 0v to 4.1V to the control system.

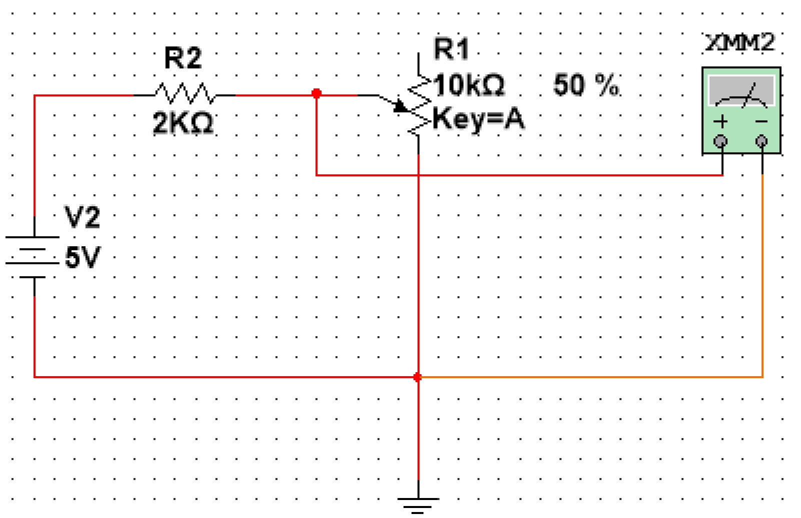

Figure 8: Potentiometer Circuit Design

9.3. Hall-Effect Sensor

The SNDH-T Series would be the superior option to build our hall-effect sensor circuit. The SNDH-T Series is a dual differential hall sensor that provides speed and direction information using a quadrature output with signals 90 phase shifted from each other. The sensor utilizes throttle potentiometers to provide the control system voltage values based on the positional input for speed control.

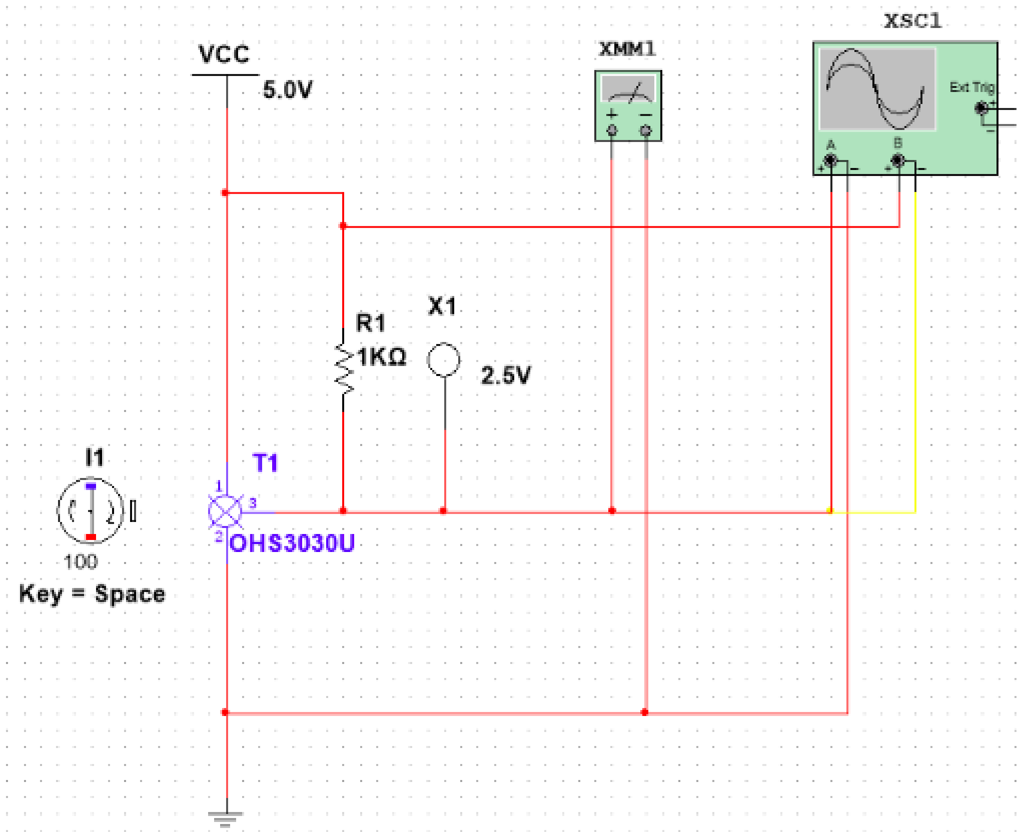

Figure 9: Hall-Effect Sensor Circuit Design

9.4. Control Software

The control software has two main components, the feedback system and the safety monitoring. The feedback system monitors the inputs of the potentiometers and the Hall-Effect sensor and is what most of the data processing concerns. When the potentiometer is read, the STM32's analog-to-digital converter (ADC) outputs a ten bit value, and three major steps are needed to turn this into a usable input.

First, the specific eccentricities of the input potentiometer need to be managed. Due to internal resistance, the output voltage of a potentiometer is not truly 0V - 5V, and this error will vary from one unit to another. To manage this, after the ten bit input value is converted into a byte of data, maximum and minimum limits are imposed at 30 and 220, roughly 30 units from the ideal minimum and maximum of 0 and 255, within the error percentage of most properly functioning potentiometers. These limits decrease and increase, respectively, as the processor encounters new input values outside the current limits. It is these limits that the processor uses when recalculating the raw input byte into a proportional, usable output byte, ensuring the measured value is processed into a byte of data reflective proportional to a true 0V - 5V input. These changing limits and their initialization allow for the system to overcome this imprecise voltage error on the edges while still processing a medium value as such even if it has not encountered a larger input yet.

The second step is the newly processed byte of data is loaded into the next byte of a 15 byte array, which has a running total. The average of the entire array is used going forward; this helps manage any outstanding measurements, smoothing the output. The third step is a proportional recalculating of the maximum limit of this average value to 200. This gives a 55 unit buffer which the user cannot enter by adjusting the mower lap bars. This space is reserved for the feedback system to enter into should more power be needed by the motors to maintain current speed going into an incline.

Once the potentiometer input has been processed, it is multiplied with the time measurement collected from the Hall-Effect sensor. This sensor features a gear with 32 teeth, and the sensor sends a high on two different output wires for when the sensor encounters a tooth and for when it encounters a valley. By measuring the time both inputs are high (note: this implementation is Arduino specific which has no usage internal timers. A simpler method would be to measure the time between the rising edge of one of the sensor's output wires), the total time between the rising edge of an encountered tooth can be determined. As the mower's top speed is required to be five miles per hour, that equates to 0.005703 seconds per such rising edge. By multiplying this number by 200, the maximum digital output that can be reached by the user under normal conditions, a ratio of 1.1406 is reached. This is the main ratio of maximum, ideal potentiometer input divided by the inverse of the Hall-Effect sensor's ticks per second, and the measured values, once multiplied, are compared against it. By this comparison, the feedback system can determine if the PWM duty cycle needs to be increased or decreased. The duty cycle has immutable enforced limits of 0 and 255 to prevent byte overflow or underflow, and to avoid any jerkiness or shocks to the system, any increase or decrease is capped at 5 units (~2%) a cycle, ensuring smooth and controlled acceleration.

As the average from the 15 byte array has limits guaranteed to be at 0 and 255, it can be compared with intermediate limits determining if the potentiometer positioning corresponds to a forward, reverse, or deadband command state. The current state is marked as one of four possible states, the three previously mentioned as well as an error state, should a value outside the expected maximum and minimum bounds be encountered. If entered, the error state and deadband state will both disable the H-bridge and force the PWM output to 0. If in the reverse state, the PWM output is reversed and halved so the closer to zero the input gets, the greater the PWM duty cycle. The duty cycle and command state are the two parts of the output parameter. With both parts of this parameter initialized, it can be provided to the Go() function which dictates which of the four H-bridge mosfets will be set to high or low, and which, if any, will receive the PWM output. Afterwards, the parameters are sent by the master to the two slaves which run a copy of the Go() function so all motors act in unison. It is also here that should the deadband or error states be encountered, the four H-bridge mosfet inputs will all be set to low. In addition to the hardware safety elements implemented to provide power for the system and the software safety checks prior to the feedback system engaging, separate internal safety checks are included at every level of the feedback control system.

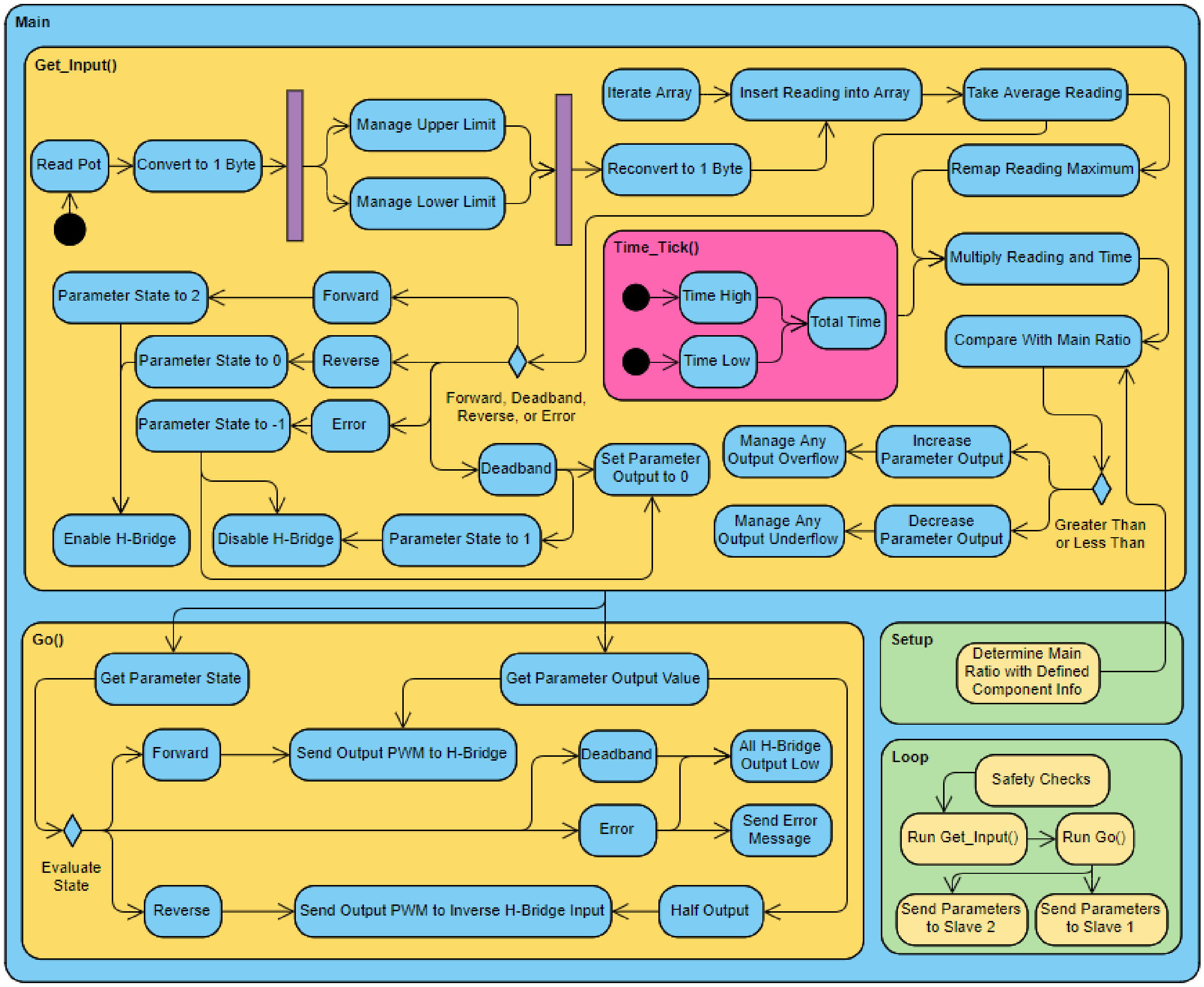

Figure 10: Control Software Activity Diagram

9.5. Output Circuitry

The first design that has been built was on a breadboard with four MOSFETS connected to an IC h-bridge which is connected to an arduino, a simplified application of the H-bridge IC shown in *Figure 10:simplified application of the H-bridge IC*. The design worked however it didn't provide a clean square wave which is what was required. Secondly, a protection circuit was added to the breadboard that consists of four extra MOSFETS that were connected in parallel to increase the current capability. After the addition the design had provided the much wanted square wave, which only concludes that the design works how it's supposed to. However, since the breadboard can not handle high currents the design couldn't be tested unless a different platform was provided. Therefore, a high current development board was assembled.

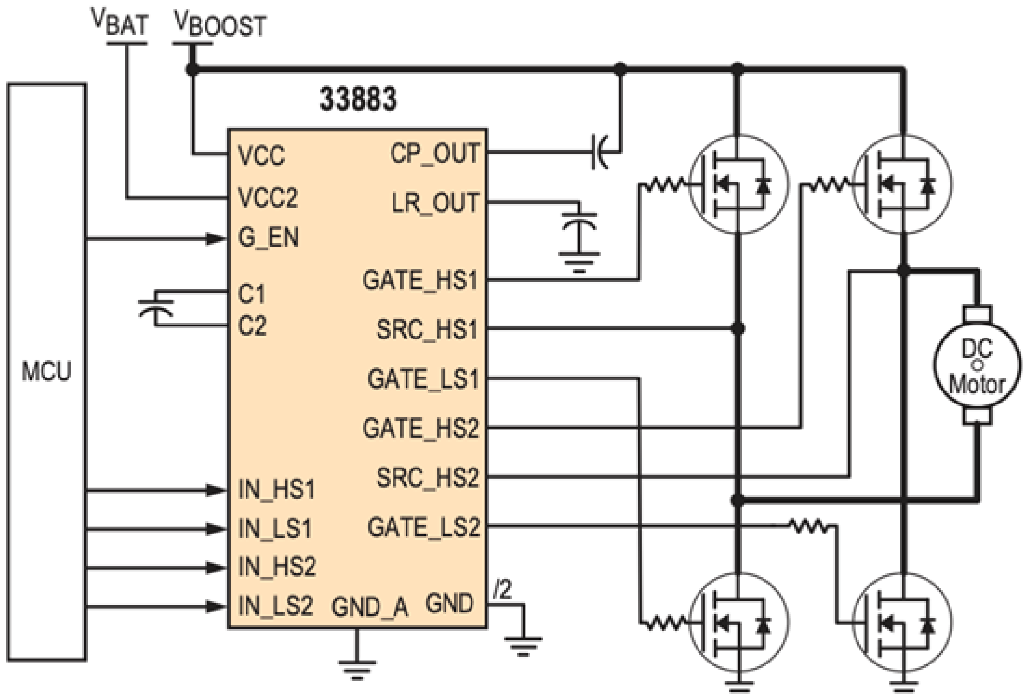

Figure 11: Simplified Application of the H-bridge IC

10.Project Potential Problems and Potential Solutions

10.1 Heat

As the motors are supplied power, they also generate heat, which if unchecked can accumulate to a level where the motors damage themselves and the other components around them. Most vehicles approach solutions for these manner of problems by ensuring sufficient airflow across the motor or liquid collant of some manner. Expense and size restrictions prohibit the latter and although some attempts can be made to provide airflow, given that the vehicle being powered is a lawnmower, the larger the airflow the greater the likelihood of various debris entering the motor and gearbox housing.

To combat this difficulty, a thermometer is present in the design to help prevent damage by notifying the user when the motor is beginning to overheat. Although this is reactive instead of preventative, it is a viable way to help extend the life of the mower.

Potential solutions for this are to make the overheat indicator LED prominent, allowing it to flash when heat is approaching dangerous levels, and to use filters and grates to help allow for some measure of airflow into the motor housing.

10.2 Testing at high current

As of this moment testing the development board at high currents is unavailable due to uncontrolled reasons and for an unknown amount of time. Even though the design works analytically and as predicted at low current, it is rather disappointing to not be able to see the design perform at its full potential.

A potential solution for this problem is to have a team pick up where we left and have them test the design and demonstrate its full potential.

11.Project Management

11.1 Scheduling

Due to the unplanned school closure the project had to be done separately and virtually, and because of that the project plan had to drastically change from what was originally scheduled. An updated project plan of the current situation is demonstrated below:

TASK DESCRIPTION	DURATION	START DATE	END DATE
Requirements Document	7	9/20/2019	9/27/2019
Scope/Background	7	9/20/2019	9/27/2019
Requirements	7	9/20/2019	9/27/2019
Test/ Management	7	9/20/2019	9/27/2019
Figures/Charts	7	9/20/2019	9/27/2019
Requirements Prestation	7	9/20/2019	9/27/2019
Preliminary Design Research	31	9/20/2019	10/21/2019
Physical and Electrical Research	31	9/20/2019	10/21/2019
Input Research	31	9/20/2019	10/21/2019
Output Research	31	9/20/2019	10/21/2019
Controls Research	31	9/20/2019	10/21/2019
Design Options Document	7	10/18/2019	10/25/2019
Physical and Electrical	5	10/18/2019	10/23/2019
Input	5	10/18/2019	10/23/2019
Output	5	10/18/2019	10/23/2019
Controls	5	10/18/2019	10/23/2019
Finalize Document	2	10/23/2019	10/25/2019
Design Options Presentation	3	10/22/2019	10/25/2019
Design Analysis	36	10/26/2019	12/1/2019
Project Design Document	11	11/25/2019	12/6/2019
Physical and Electrical	11	11/25/2019	12/6/2019
Input	11	11/25/2019	12/6/2019
Output	11	11/25/2019	12/6/2019
Controls	11	11/25/2019	12/6/2019
Finalize Document	4	12/2/2019	12/6/2019
Project Design Presentaion	4	12/2/2019	12/6/2019
Build Concept Prototype	32	1/13/2020	2/14/2020
Purchase Prototype	4	1/13/2020	1/17/2020
3D Print Prototype	18	1/13/2020	1/31/2020
Assemble All Parts	6	2/1/2020	2/7/2020
Integrate Software	6	2/8/2020	2/14/2020
Testing Prototype	48	2/15/2020	4/3/2020
Safety Circuit	27	2/15/2020	3/13/2020
Potentiometer Circuit	27	2/15/2020	3/13/2020
Hall-Effect Sensor	27	2/15/2020	3/13/2020
Control Software	38	2/15/2020	3/24/2020
Output Low Current Circuit	27	2/15/2020	3/13/2020
High Current Development Board	21	3/13/2020	4/3/2020
Project Report	21	3/13/2020	4/3/2020
Project Poster	7	4/1/2020	4/8/2020
Project Presentation	1	4/23/2020	4/23/2020
Project Demo	1	5/1/2020	5/1/2020

Figure 12: Project Plan Gantt Chart

11.2 Project Schedule Task

Tasks	Subtasks	Start time	End time	Responsible	Collaborators
Requirements Document		09/20/2019	09/27/2019	All	All
	Scope/ Background	09/20/2019	09/27/2019	Tim Ishmael	Yuyang Weng
	Requirements	09/20/2019	09/27/2019	Nuha Alshaibani	Nate Tippery
	Test/ Management	09/20/2019	09/27/2019	David Myrick	Yuyang Weng
	Figures/Charts	09/20/2019	09/27/2019	Yuyang Weng	
Requirements Presentation		09/20/2019	09/27/2019	All	All
Preliminary Design Research		09/20/2019	10/21/2019	All	All
	Physical and Electrical Research	09/20/2019	10/21/2019	Yuyang Weng	David Myrick
	Input Research	09/20/2019	10/21/2019	Nate Tippery	
	Output Research	09/20/2019	10/21/2019	Nuha Alshaibani	David Myrick
	Controls Research	09/20/2019	10/21/2019	Tim Ishmael	David Myrick

Design Options Document		10/18/2019	10/25/2019	All	All
	Physical and Electrical	10/18/2019	10/23/2019	Yuyang Weng	David Myrick
	Input	10/18/2019	10/23/2019	Nate Tippery	
	Output	10/18/2019	10/23/2019	Nuha Alshaibani	David Myrick
	Controls	10/18/2019	10/23/2019	Tim Ishmael	David Myrick
	Finalize Document	10/23/2019	10/25/2019	David Myrick	All
Design Options Presentation		10/22/2019	10/25/2019	All	All
Design Analysis		10/26/2019	12/01/2019	David Myrick	All, Eric Phanco
Project Design Document		11/25/2019	12/06/2019		
	Physical and Electrical	11/25/2019	12/06/2019	Yuyang Weng	David Myrick
	Input	11/25/2019	12/06/2019	Nate Tippery	
	Output	11/25/2019	12/06/2019	Nuha Alshaibani	David Myrick
	Controls	11/25/2019	12/06/2019	Tim Ishmael	David Myrick
	Finalize Document	12/02/2019	12/06/2019	David Myrick	All

Project Design Presentation		12/02/2019	12/06/2019	All	All
Project Design					
	Safety Circuit	01/20/2020	03/13/2020	Yuyang Weng	Nate Tippery
	Potentiometer Circuit	01/20/2020	03/13/2020	Nate Tippery	Yuyang Weng
	Hall-Effect Sensor	01/20/2020	03/13/2020	Nate Tippery	Yuyang Weng
	Control Software	01/20/2020	03/24/2020	Tim Ishmael	David Myrick
	Output Low Current Circuit	01/20/2020	03/13/2020	Nuha Alshaibani	David Myrick
	High Current Development Board	03/13/2020	04/03/2020	David Myrick	
Project Report		03/12/2020	04/03/2020	All	All
Project Poster		04/23/2020	04/23/2020	All	All
Project Presentation		05/01/2020	05/01/2020	All	All
Project Demo		05/01/2020	05/01/2020		

Table 7: Project Schedule Task

12.Implementation Details

12.1 Safety Circuitry

The implementation of the first design of the safety circuitry is shown in *Figure 13: Safety Circuit on Breadboard.*

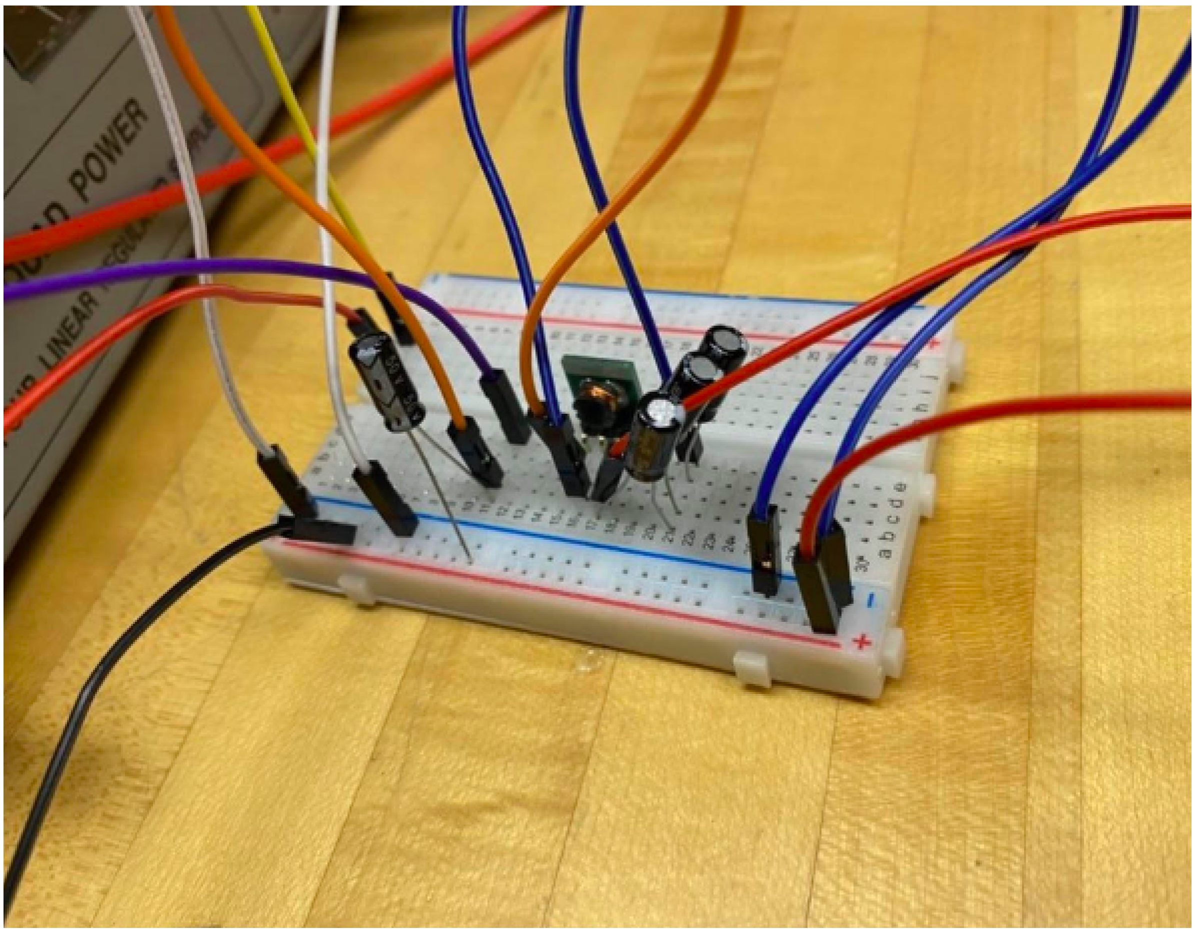

Figure 13: Safety Circuit on Breadboard

After testing the safety circuit, outputs worked as predicted with low current. And the schematic of the safety circuit was created on Multisim. It shows all the components and connections. The schematic of the safety circuit on Multisim is shown in *Figure 14: Safety Circuit on Multisim.*

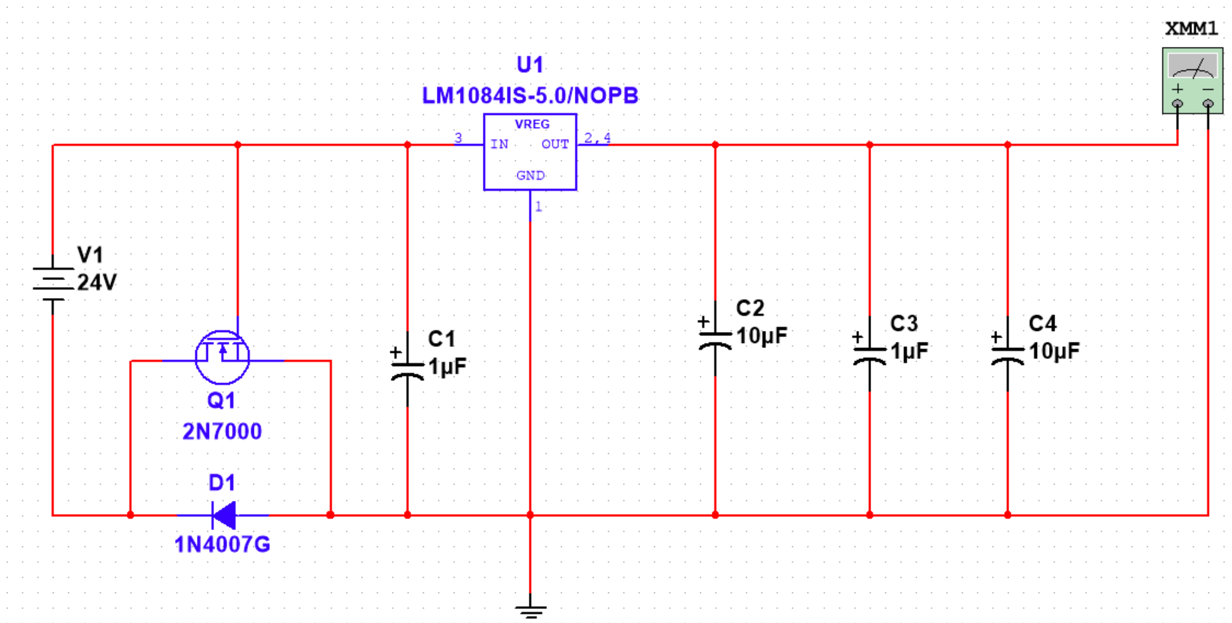

Figure 14: Safety Circuit on Multisim

12.2 Potentiometer Circuit

After testing the potentiometer circuit, outputs worked as predicted with low current. And the schematic was created and tested on Multisim. *Figure 15: Potentiometer Circuit on Multisim* shows all the connection and the components.

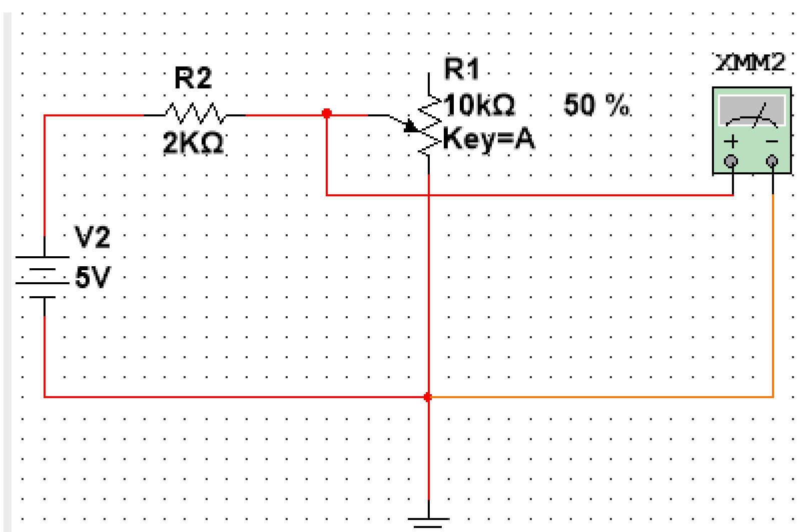

Figure 15: Potentiometer Circuit on Multisim

12.3 Hall-Effect Sensor

After testing the hall-effect sensor, outputs worked as predicted with low current. And the schematic was created and tested on Multisim. *Figure 16: Implement Hall-Effect Sensor Circuit on Multisim* shows all the connections and components for hall-effect sensor circuit design.

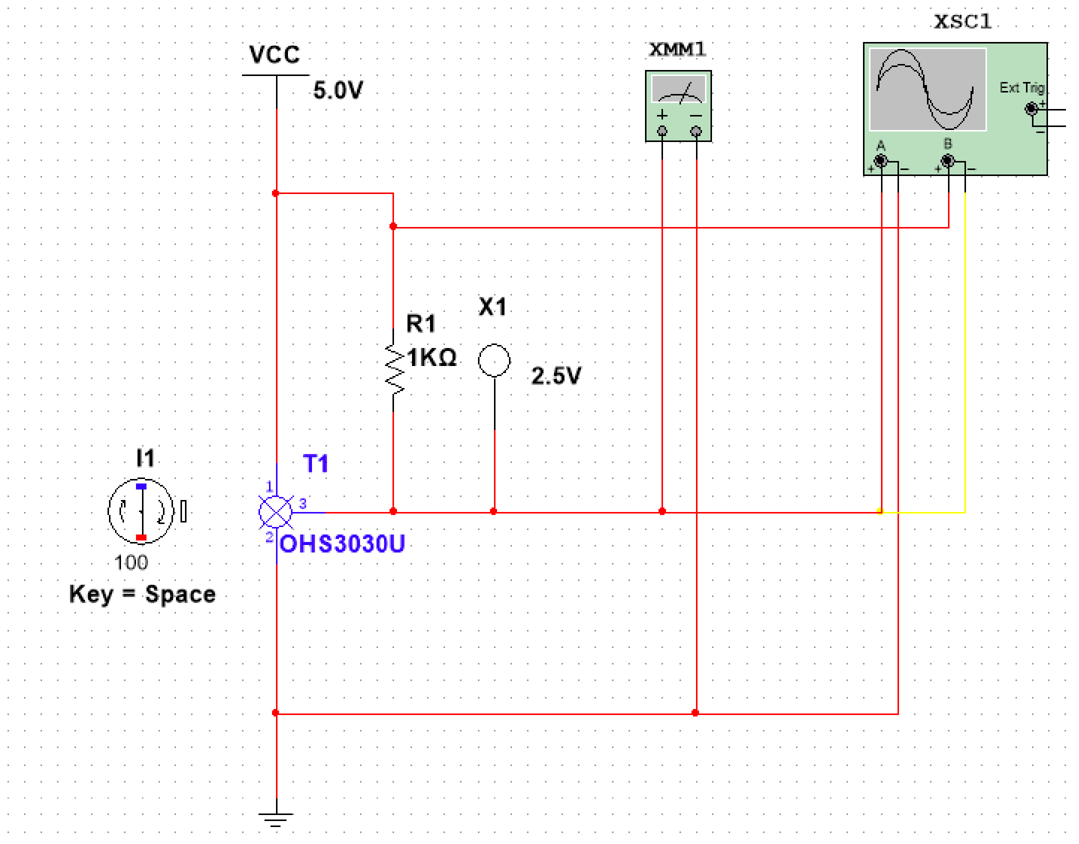

Figure 16: Implement Hall-Effect Sensor Circuit on Multisim

12.4 Control Software

The control software was written with standard Arduino libraries as the flash memory of the STM32s is sufficient in size to contain the whole of the code.

12.5 Output Circuitry

The implementation of the first design with the four MOSFETS is shown in *Figure 17:simplified application of the H-bridge IC on breadboard.*

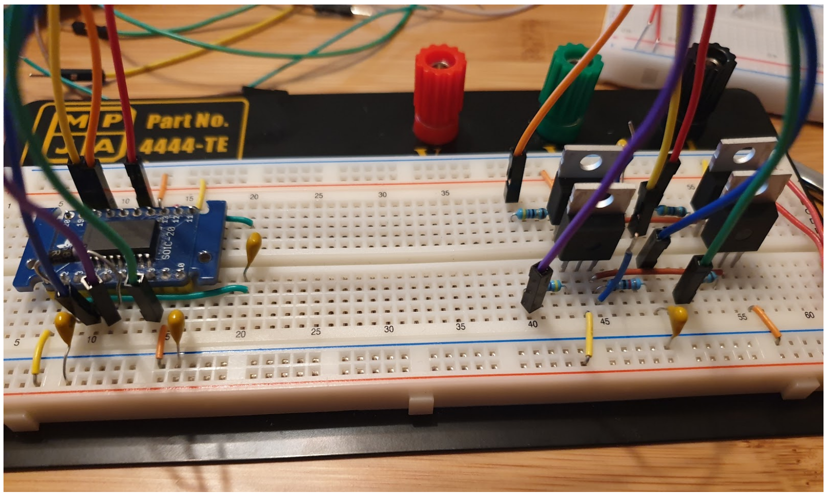

Figure 17: Simplified Application of the H-bridge IC on Breadboard

After knowing that the full circuit was a success when testing with low current, a PCB design schematic was created, however due to time constraints an actual PCB was not ordered. Moreover, the schematic shows all the connections and the additions that were made to the design. The schematic is shown in *Figure 18: PCB Schematics of the Output Circuit.*

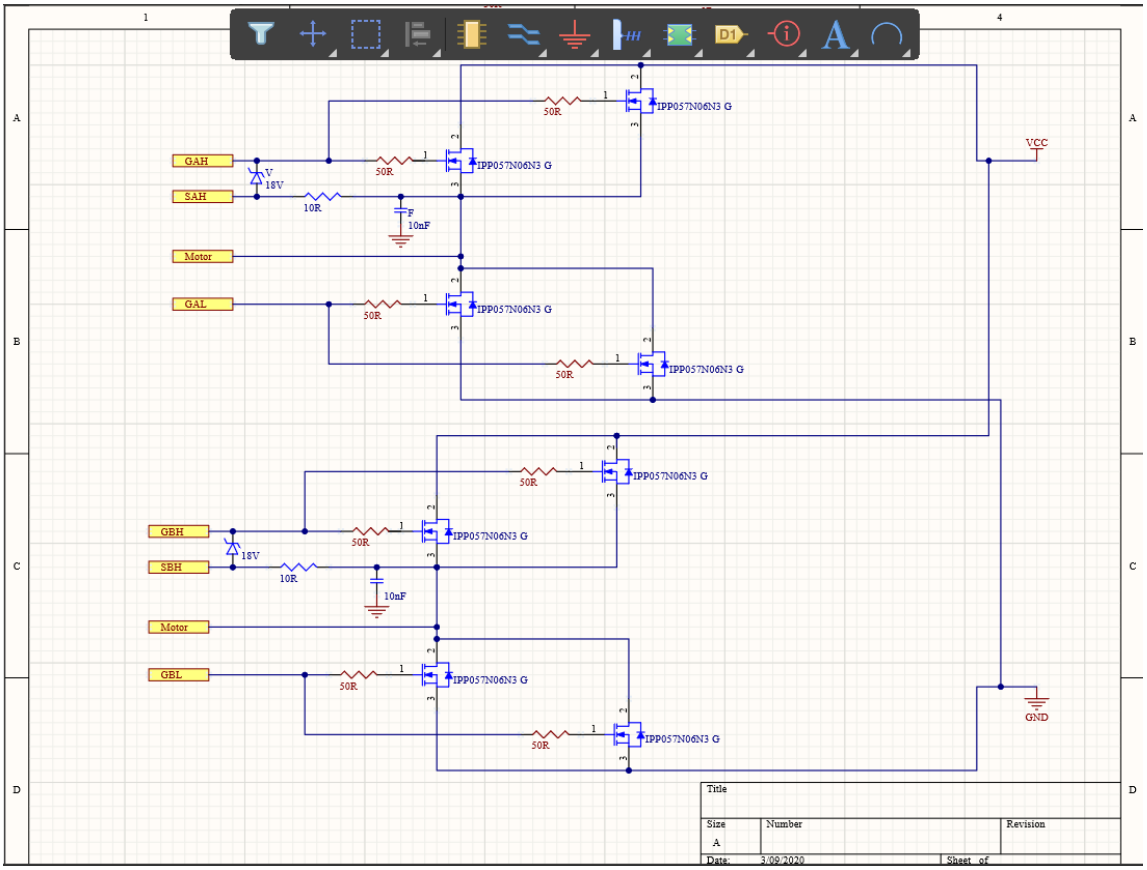

Figure 18: PCB Schematics of the Output Circuit

13.Testing Procedures and Results

13.1 Safety Circuitry

When voltage greater than what components on the circuit required, the voltage regulator keeps voltage close to a desired voltage to avoid the overload. And the final output voltage will be 5V, shown as *Figure 19: Output When the Voltage Greater than Circuit Required* .

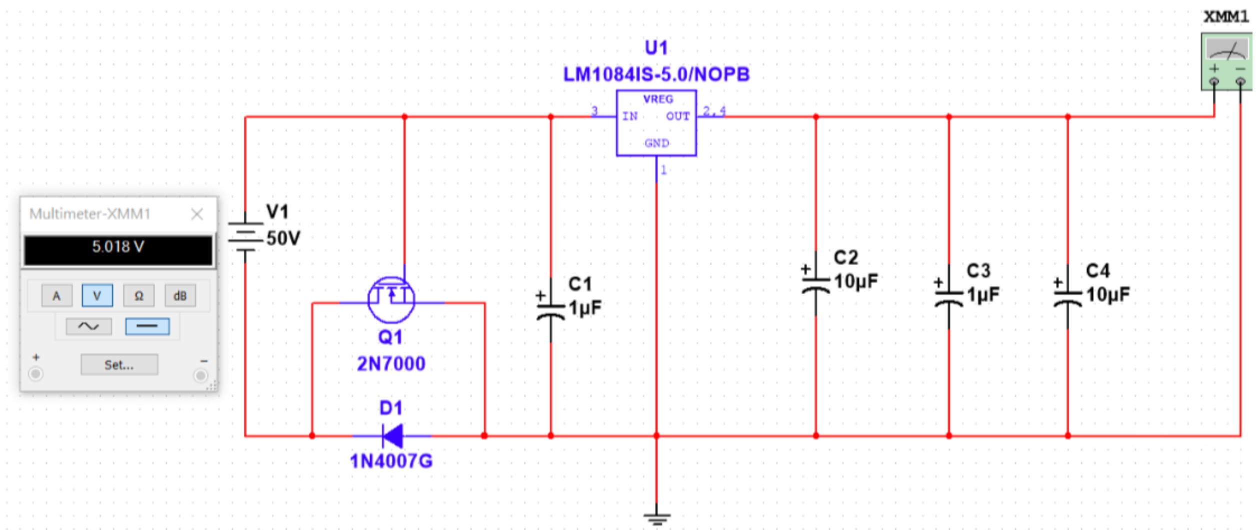

Figure 19: Output When the Voltage Greater than Circuit Required

When the battery is installed properly and the portable equipment is powered, the N-MOSFET's gate voltage is taken high and its channel shorts out the diode, Therefore the final output will be 5V. Show as *Figure 20:Output When Battery is Installed Properly.*

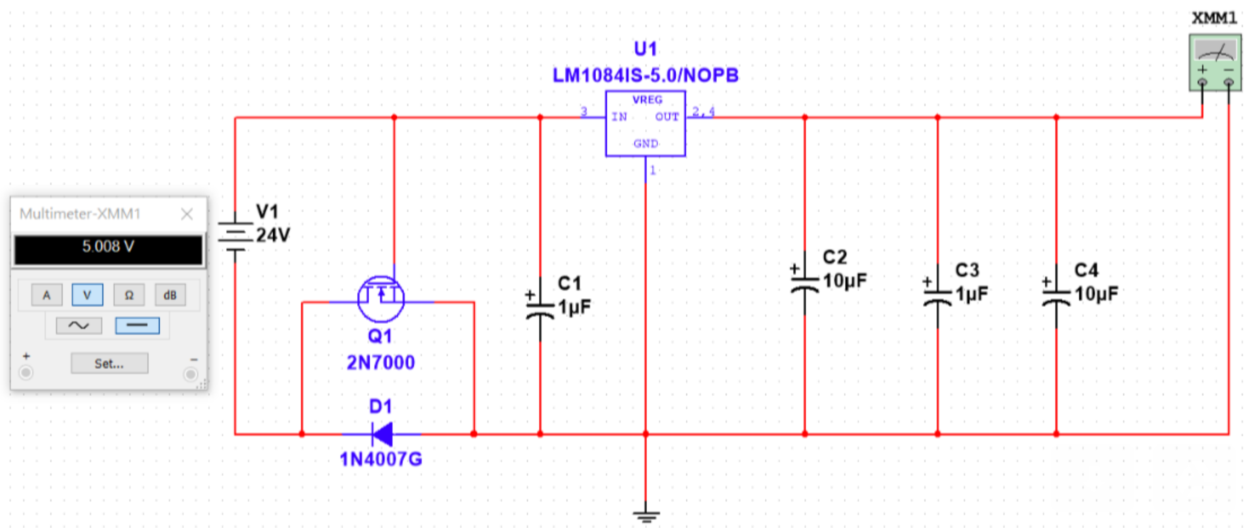

Figure 20:Output When Battery is Installed Properly

When the battery is installed incorrectly, the N-MOSFET's gate voltage is low, preventing it from turning on, and the final output will be 0V.Show as *Figure 21:Output When Battery is Installed Incorrectly.*

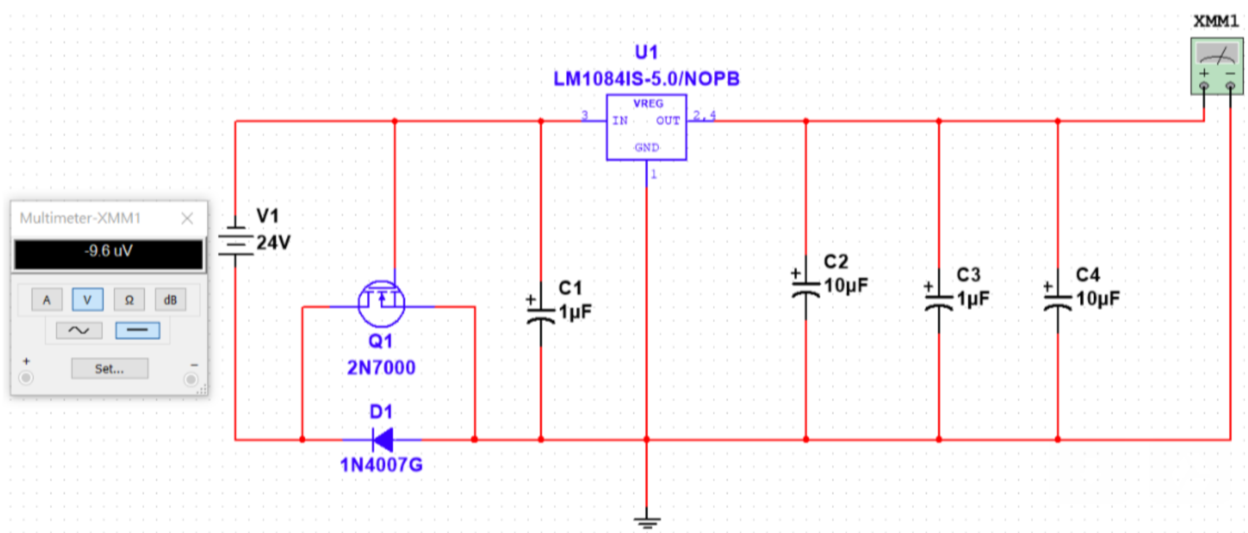

Figure 21:Output When Battery is Installed Incorrectly

13.2 Potentiometer Circuit

The voltage output range for the potentiometer is from 4.167V to 0V. When whole spin the output voltage will be 4.167V shown as *Figure 23: Potentiometer Output Voltage for Whole Spin.*When halfway the output voltage will be 3.571V shown as *Figure 22:Potentiometer Output Voltage for Halfway.*

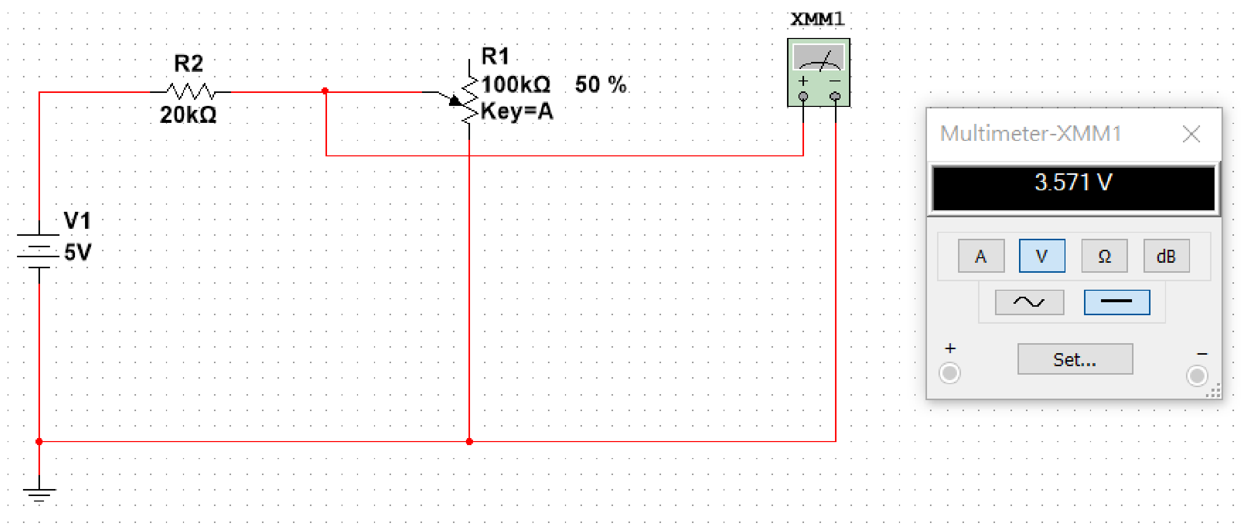

Figure 22:Potentiometer Output Voltage for Halfway

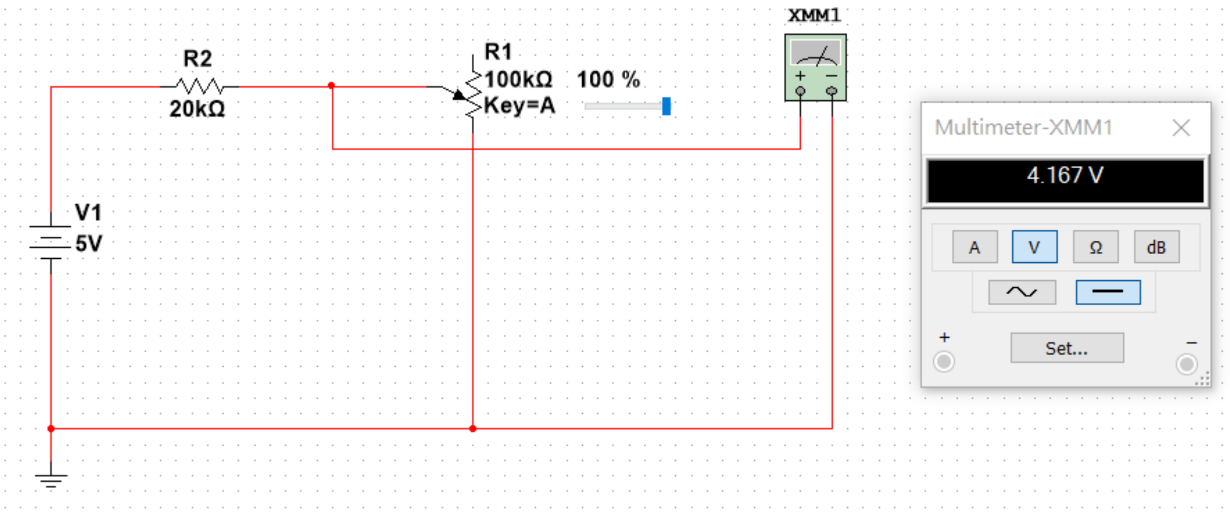

Figure 23: Potentiometer Output Voltage for Whole Spin

13.3 Hall-Effect Sensor

Hall-effect sensor outputs two different square digital signals 5V and 0V. The figure below shows the simulation of the hall-effect sensor in Multisim. The magnetic flux source uses a key to change the density and polarity of the magnetic flux impacting on the Hall-effect sensor in Multisim.

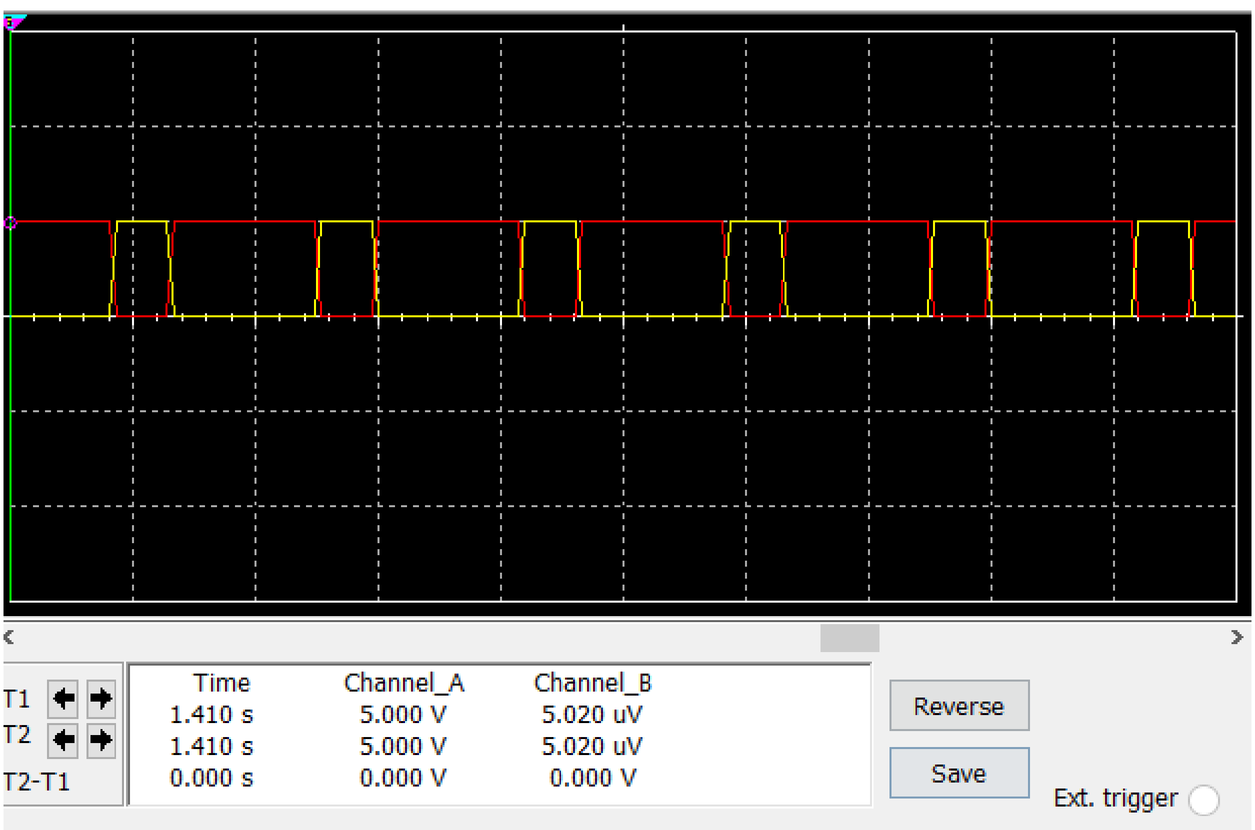

Figure 24: Simulation of the Hall-Effect Sensor in Multisim

13.4 Control Software

Since the Arduino framework lacks a dedicated debugger, most of the control system testing was done through white box testing and print output statements. The PWM outputs and H-bridge enable/disable have been tested via LED output with potentiometer input, and the serial communication from the master controller to the slaves has been tested. Further testing will require the integration of Hall-Effect sensor and motor driver and will be black box testing to determine anticipated performance of the proportional-integration-differentiation (PID) control logic.

Testing of the feedback system's allowance into the 55 unit buffer above which the user can access will need to be tested via simulation due to restrictions on physical testing. These restrictions also prohibit black box testing of the thermometer input.

13.5 Output Circuitry

The hardware testing procedure that was used to test the breadboard in the first and second implementation was using an oscilloscope to see if the design had provided the square wave as predicted. A multimeter was also used to measure the current as voltage was increased on the connected power supply. As for the results the second implementation has provided a cleaner square wave which is what was wanted.

A simulation was created to show that the design does indeed work and gives the expected output. However, because it is a simulation design the h-bridge and the STM32 code that is connected were alternated for a pulse voltage instead to give the same result as the design. Therefore, the PWM signal that was pushed by the h-bridge would be mimicked. This is shown in *Figure 25 : Simulation Schematic of the Output Circuit on Multisim.* And the result is shown in *Figure 26: Result of Simulation Schematic of the Output Circuit on Multisim.*

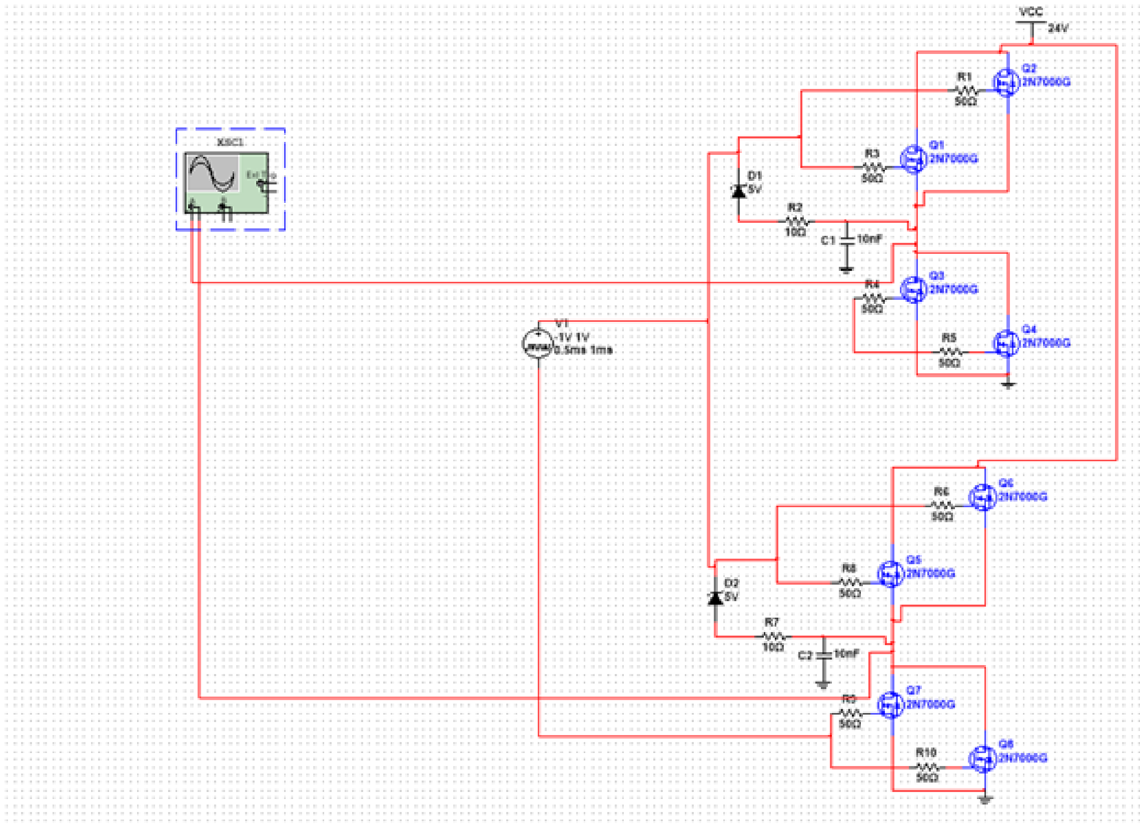

Figure 25 : Simulation Schematic of the Output Circuit on Multisim

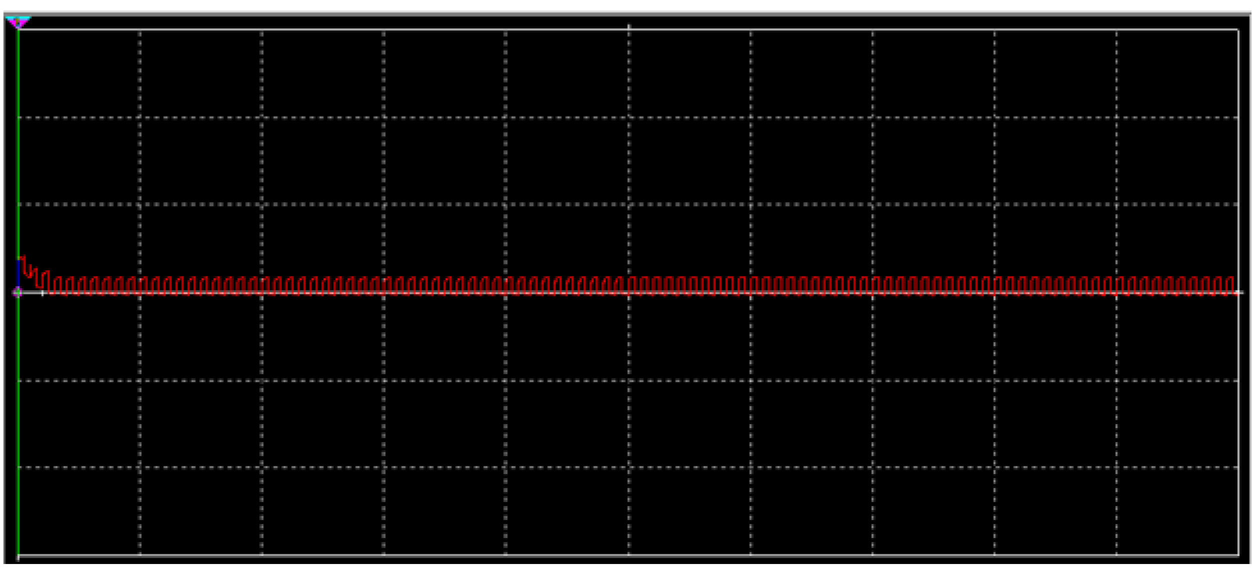

Figure 26: Result of Simulation Schematic of the Output Circuit on Multisim

13.6 High Current Development Board

Final testing will be completed on a high current development board. The use of this board will allow high current PWM signals to be generated so the design can be observed under a realistic load. The components chosen will allow currents not tolerated with traditional breadboard. Under these conditions data will be collected to finalize control parameters such as RPM output of the motors and fine tuning of speed adjustment functions. This testing was put on hold due to restrictions on travel.

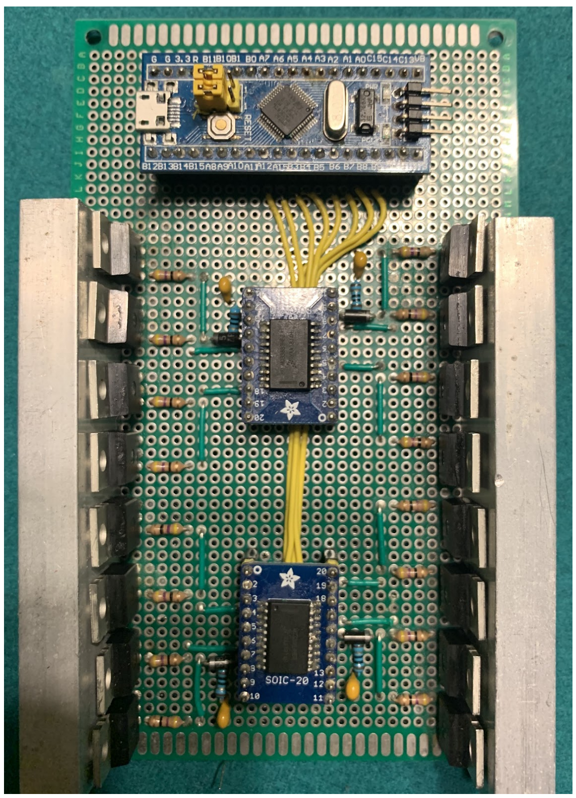

Figure 27: High Current Model (above)

The layout of this model was designed around heat displacement and protecting sensitive components from the output current required to meet motor requirements. Each high current model has the capability to provide output to two brushed DC motors. The H-bridge devices were wired in opposite directions to ensure that only four MOSFETs would be powered per heat sink at any given time. Bus lines for voltage and ground still need to be implemented in this model and will be updated upon completion.

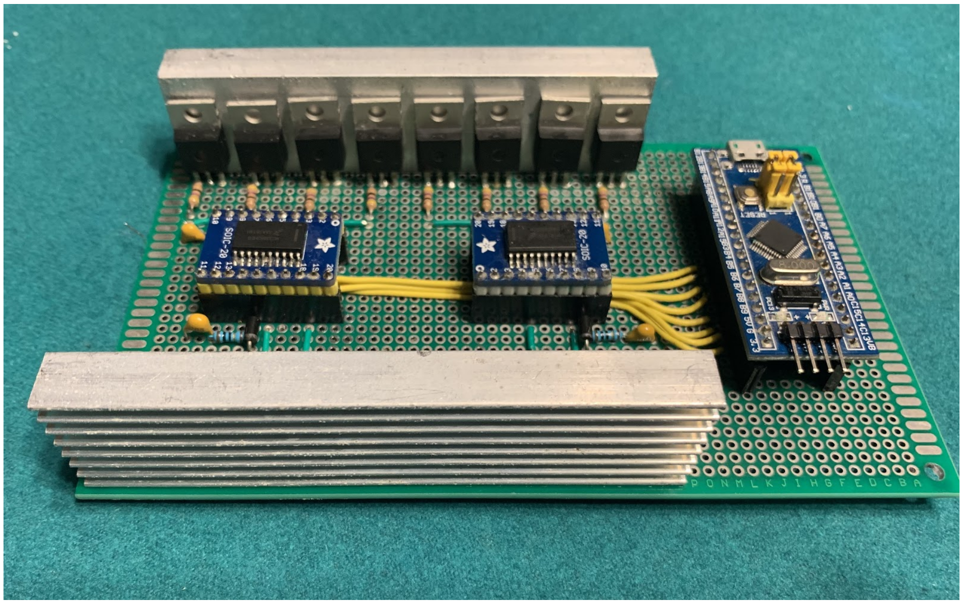

Figure 28: High Current Model (side)

14.Conclusion and Future Work

14.1 Conclusion

In conclusion, the system that was created includes multiple subsystems; input, output, and the control subsystem, all these subsystems are in charge of supplying a high current to power a DC motor, while having a varying speeds controlled by a potentiometer. The design that was assembled in this course is able to fulfil the requirements that were expected considering the unplanned events that had occured. And the results that were obtained were as expected.

14.2 Future Work

Future work that can be picked up is to create the design on a high endurance board and properly test it at high level currents and see how it holds. Also, another possible work that can be done in the future is changing the brushed DC motors to brushless DC motors and configure a design to achieve it. Also, compare both the brushed DC motor design and the brushless DC motor design on how both work and on what type of results each provides.

15. List References

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16. Appendices

16.1 Program Used

- Multisim
- Altium
- Excel
- Google Drive
- Arduino IDE
- Online Visual Paradigm

16.2 List of Abbreviations

DC – Direct Current

AC – Alternating Current

PWM – Pulse Width Modulation

MOSFET – Metal Oxide Semiconductor Field Effect Transistor

IC – Interstitial Cystitis

LED – Light Emitting Diode

USART - Universal Synchronous/Asynchronous Receiver/Transmitter

CPU – Central Processing Unit

SWD – Serial Wire Debug

ADC – Analog to Digital Converter

PID - Proportional-Integration-Differentiation

PCB – Printed Circuit Board

16.3 List of Materials

8x TO220 N-ch mosfets 60V 80A IPP057N06N3 G

8x 0805 50ohm resistor

2x 0805 10ohm resistor

2x 0805 10nF 50V ceramic capacitor

2x 18v zener diode 0.5W ZMM5248B

1x nxp MC33883 H-bridge gate driver

1x 0805 33nF 50V ceramic capacitor

2x 0805 470nF 50V ceramic capacitor

1x generic through-hole polarity protection diode

1x 3pin dc/dc converter max 36vin 5v out VXO 7805-500

3x smd 10uF 50V 5x5.3mm electrolytic capacitor

3x 0805 1uF 50V ceramic capacitor

9x 0805 10k resistor

4x 0803 3k resistor

2x 10k through-hole trimmer potentiometers

8x Heatsinks

3x STM32 Card

1x Development Board