

BRUSHLESS DC MOTOR FOR TEACHING

A Research Paper submitted to the Department of Electrical and Computer Engineering
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Electrical Engineering

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By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISOR

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Statement of Work

Chase Carson

My main responsibility was the PCB design, but I also helped plan the embedded code architecture and made the CAD drawings of our system. These drawings were very useful for communicating our progress, and also made the 3D printing and mechanical manufacturing very straightforward. I was in contact with our machining partner Sebring Smith from Lacy Hall, who oversaw the cutting of laminations and the filing of the steel afterwards.

Our design utilized various premade chips that were not available in our current Multisim library, so I initialized the part files in Multisim for planning the physical layout of the board. With the size constraint of the entire PCB and the extensive connections that must be made with a 3-phase electromagnetic circuit, the traces and spacing on the board were difficult to successfully implement.

My role for the PCB design consisted of designing the schematics, board layout and routing, tracking and ordering parts for the bill of materials (BOM) in Digikey and McMaster-Carr, and soldering both boards. The overall process included making two PCBs: a main board and the Hall effect board. The first Hall effect board had to be modified after a change in mechanical design, so I also composed the new Hall effect PCB to satisfy updated constraints. I also tested both of the PCBs' electrical connections to verify the correct traces for controlling the motor.

For final testing stages of the motor, I assembled the fully functioning system, assisted with the C coding and took the various videos for the final demonstration video. Supplemental tasks included driving to pick up PCBs from WWW manufacturing and physical modifications to the system in testing stages and fixing mechanical issues that arose.

Gracie Judge

My main responsibility was the mechanical and magnetic design of the motor. This included determining the physical parameters of the motor, determining what wire and winding pitch to use, and the calculations to predict the performance of the motor. These dimensions were added to the CAD drawings.

Our design was set to be 9 slots and 8 poles, meaning 9 spokes protruded from the motor and 8 rotating magnets were stuck within the circumference of the stator on the rotating piece. The rotor was chosen to be within the stator because it is safer to have the moving part farther from human contact in the lab. Additionally, a very useful textbook was found for brushless DC motor design that used this setup exclusively. Other design improvements included notching the rotor for easy magnet removal and curving the spokes on the stator to make an air gap more flush with the radius of the rotor.

With the dimensional parameters set and the steel laminations cut, I wound the 1000+ coils by hand. The first try doing this we encountered the problem of the rough steel cutting through the insulation of the magnetic wire. We solved this problem by unwinding the motor, sanding down the stator, 3D printing plastic bobbins, and then encasing the steel. With this new setup due to mechanical complications, the new dimensions for windings gave me the opportunity to wind the 1000+ coils by hand again.

Since I was working remotely for the second half of the semester, I also took on writing this final report and composing the final demonstration video. This allowed team members in Charlottesville to focus on physical testing of the motor and associated firmware.

Adam McGill

My main responsibility was implementing a speed controller using the microcontroller. Proper controlling of the motor commutation allows the user to fully interact with the motor. The required embedded coding has comprised the body of my work this semester. After the team decided on the inputs and outputs to the controller, the larger software architecture had to be selected. I created a detailed block diagram demonstrating the major software design blocks, as well as a document cataloging the specific design decisions. With the design planned, I wrote the code to control the outputs to the motor drivers, display information about the motor on the OLED, and respond to the buttons on the hardware interface.

To implement the desired functionality of the speed controller, a finite state machine was programmed to keep track of the electrical state of the motor. Additionally, I initiated and implemented the I²C protocol to communicate with the OLED using available libraries modified by Chase. After that I programmed the button debounces, configured the hardware for the pulse width modulation (PWM) schemes, and wrote specific interrupts. In the process of writing the code, I adhered to the coding conventions established in our Capstone class (ECE 4440/4991), including the comment format for functions and files. Since I wrote the overall project test plan, testing the firmware was also my responsibility. The previously mentioned individual functionalities were tested by observing the correct outputs for inputs from the Hall Effect sensors, accurately displaying information on the OLED, responding properly to the buttons. In addition to testing isolated subsystems, I also evaluated the system's cohesive function.

The remainder of my time was devoted to further testing and refining the code. For instance, I further organized the responding of the speed controller to separate Hall Effect readings into a matrix based on the mechanical and electrical states. Optimization involved cleaning up the code and getting the interrupt service routines to run as quickly as possible by cutting out any redundant steps and making any function calls inline.

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Abstract

Electromagnetic circuitry allows motors to convert applied electrical energy to induced mechanical energy; the application of electromechanical systems can be seen in most modern industrial processes such as power electronics, automobiles, and aircrafts. Despite their role in establishing a deep-rooted understanding of power electronics, the concepts of electromagnetism can be hard for students to grasp and visualize while exploring motor designs. The goal of this project was to design a brushless DC (BLDC) motor that is interactive and informative for classroom instruction.

The proposed system consisted of two main components: an electronic speed controller, and the motor. The motor consists of a stationary stator with nine steel spokes wrapped with magnetic copper wire. Inside the radius of the stator is the rotating steel with eight magnets attached. The design of the speed controller was implemented on a printed circuit board (PCB) with a connected microcontroller.

Background

The University of Virginia offers a class, ECE 3250/3251, which explores electromagnetic motor material in depth. The class requires a corresponding lab section for students to gain hands-on experience with energy conversion. When covering the topic of motors, the only DC motor for students to observe in the lab currently is a standard *brushed* DC motor. However, due to sliding brushes, which result in friction wear and dangerous sparking, brushed DC motors incur a lot of power loss in their operation. To avoid a lossy design, a DC motor was designed that operates in a manner similar to the AC synchronous machines also covered in this class. The brushless DC motor (BLDC) offers near silent operation, fewer losses, less maintenance, electronic control, and a better weight to power ratio than the standard brushed motors [1].

The goal of this capstone project was to build a brushless DC motor to be used in the Electromagnetic Power lab at the University of Virginia. The motor design was done to display operation data for teaching purposes. Ideally, a student in the power lab will be able to control the motor parameters and watch the relevant parameters of the motor change in front of them. Therefore, the plan of the group was to build a brushless DC motor, speed controller, and hardware interface to control the motor and display relevant values. The internal operation of the motor was to be as visible as possible and the interface display was to be as informative as possible.

Controlling a BLDC motor with electronic speed control circuitry is not a new idea [2], but this proposed system will be built specifically for instructional purposes. This specific motor design will include an interface for instructional purposes to be used in the power laboratory at the University of Virginia. This includes LED output to demonstrate the powering of coils, speed output in RPM on the graphical interface, SPI and RS232 interfaces for future customized user interfaces, and probes to measure back electromotive force (EMF) and rotating DC voltage on the coils [3].

Previous works were considered when examining potential intellectual property concerns at a later point in this report [4]. While there are several apparatuses claimed to aid in class instruction of electromagnetic and mechanical concepts, none of them were as all-encompassing

as the project proposed through this capstone. The visibility of the motor components using plexiglass mounts, the electronic speed control options, and the demonstration of Back EMF were all unique to this specific BLDC design. The expansive integration of subsystems to the design was to further break down hard concepts to students in the lab.

This design of a BLDC motor utilized concepts from several classes taught at the University of Virginia, all of which are summarized in the Table 1 below. The project was introduced to the group by Dr. Powell of the Charles L. Brown Electrical and Computer Engineering Department.

Table 1. Summary of Previously Covered Material

Class Number	Class Name	Knowledge Provided for this Project
ECE 2630	Fun 1	Basic circuit theory used for PCB design
ECE 2660	Fun 2	Transistor circuits and LED output used for PCB design
ECE 3750	Fun 3	Complex system controls, voltage regulation, and power supplies used for PCB interconnections and design
ECE 3250	Electromagnetic Energy Conversion	Motor design theory, electromagnetics, electromechanical systems, lamination design, optimization in power systems used for design of our mechanical system
ECE 3209	Electromagnetic Fields	Magnetic theory used for the design of the mechanical system and the back EMF monitoring for the PCB design
ECE 3430	Embedded Computer Systems	TI launchpad and CCS exposure, SPI communication, PWM concepts, timing diagrams
ECE 4501	Advanced Computer Systems	Embedded system architecture, multitasking, interrupt handling, and real-time scheduling

Constraints

Design Constraints

This project went beyond basic electrical and computer engineering concepts by incorporating mechanical power ideas as well with the motor. By building a motor "from scratch" there were more space and cost restraints as opposed to buying a pre-configured one.

CPU Limitations

Texas Instruments' MSP430F5529 microcontroller was selected for the speed controller because it has separated I²C and SPI busses [4]. One output for the motor's speed in RPM was

programmed using I²C, while another output was routed to the SPI port for expansion with future projects in the lab. Additionally, the 5 timers on the board allowed for the required timing of the 2 timers for the PWM on the coil, 1 timer was used for RPM calculation, and 1 timer for the buttons. This breakdown saved an extra timer for future use.

Software Availability

UVA's software license provided the opportunity to use National Instruments' Multisim [5] and UltiBoard [6] tools to design the required boards. Additionally, Code Composer [7], a free embedded programming suite from Texas Instruments, was compatible with the selected microcontroller and made the coding more convenient.

Manufacturing Limitations

Constraints were placed upon the PCB design by the provided manufacturer, Advanced Circuits. Advanced Circuits offer a group deal for students' designs which must adhere to specific four-layer guidelines. These guidelines did not ultimately affect the main PCB design beyond dimensional constraints.

However, the Hall Effect circuitry required a circular shaped PCB to rest beneath the rotating magnets. The depth of the screws protruded beneath the rotor, which would scratch and potentially destroy a non-circular PCB. Advanced Circuits would not offer the discount for non-rectangular boards. This resulted in the design of a square-shaped Hall Effect PCB without traces around the corners of the board. The lack of traces allowed the board to be filed into the shape of a circle to meet the system's mechanical limitations.

Economic and Cost Constraints

Five hundred dollars were allotted for this BLDC motor and speed controller, which was a limiting factor of the design. This restricted the supplemental parts needed in the event of device malfunction. It also required purposeful engineering to propose different methods at lower costs. This included contacting sponsors and friends of UVA for the Silicon Steel laminations, machining devices, and 3D printing of bobbins.

In order to cut through the steel there were also guidelines met for the OMAX Maxiém 1515 Waterjet Cutter (cut kerf of 0.05”) to ensure clean cuts on the laminations [8]. A standard lathe machine was used to sand down the rotor in order to achieve a proper distance between the stator and magnets.

The availability of component parts was not an issue since most of the desired parts were very common; the most difficult part of the system to obtain was cost-effective steel for the laminations. Other parts of the mechanical system proved to be expensive as well, like the magnets and magnetic wire. All of these parts are referenced in the technical description of the project.

External Standards

The follow standards applied to this project:

1. The voltage was supplied from a 24 V DC supply in the power lab, this determined how much current would flow safely through the system for use in the lab [9].

2. *IPC-6012 Class 2/3A standards* - The board also complied with circuit board standards by using the board manufacturer Advanced Circuits [10]. Advanced Circuits' requirements determined the part and trace spacings on the developed PCBs for the project [11]. Other restrictions included hole sizes, dielectric thickness, plating, and tensile strength of the board [12].
3. *SMD Component Packages* - The industry standards define the sizing for surface mount technology (SMT) [13]. This simplified the design of the PCBs by offering footprints in Multisim. Everything but the resistors for the back EMF, the microcontroller connections, and voltage input were surface mount.
4. *I²C communication Standard* - the output to the OLED driver [14] complied with the I²C communication standard [15] and utilized the hardware port on the MSP430 microcontroller [4].
5. *Serial Peripheral Interface (SPI) Communication Protocol* - SPI standard was met to synchronously communicate with other hardware in the future [16].
6. *Universal Asynchronous Receiver/Transmitter (UART) Standard*- This was broken out to allow the SPI to properly interface with desktops in the future. This allowed the option of writing and reading between an external device and the motor's operating system. It required specific voltages and pin protocols [17].
7. *Electronics Industries Association RS232 Connection Standard* - This standard was used to break out future communication between other hardware and the MSP430 microcontroller using an RS232 cable [18]. This standard defined the connection parameters and pin layout for the communication to successfully occur [19].

Tools Employed

Various tools were used in the programming, designing, and testing of this project. The tools for the three distinct sections are outlined in detail below.

Hardware

National Instruments' Multisim [5] and Ultiboard [6] tools were used to design the boards and schematics. Chase, the primary user of these tools, was very familiar with PCB design through his prior coursework and research experience. These tools streamlined the manufacturing of the specific PCBs with help from Dr. Powell.

Firmware

The firmware, or embedded code, was written in C using the integrated development environment from Texas Instruments, Code Composer Studio (CCS) [7]. One team member's previously designed libraries for certain components made the testing and programming more efficient, since no external libraries were used.

Mechanical

In order to develop the 3D CAD files for the printing and cutting of laminations, Autodesk Inventor Pro® software was installed [20]. Various shop tools were used to cut through the dense material including the waterjet cutter [8], lathe, and assorted drill bits. Furthermore, the 3D printing was primarily done with the use of a personal 3D printer and code which converted 3D models into G code for printing [21, 22]. Additionally, basic MATLAB [23] scripts were used to calculate the depth and length of the coil windings.

Demonstration

For the final presentation of the project, a short video was made to explain the planning, programming, and construction processes used for the project. This was done by capturing video on standard iPhones [24]. The video and audio files were compiled using iMovie [25], and the final video can be viewed [here](#).

Ethical, Social, and Economic Concerns

This design raised ethical, social, and economic concerns for the prospective mass production. The concerns for six distinct subsections are explained below.

Environmental Impact

In terms of environmental impact, the materials used for the electromagnetic circuitry are the biggest concern. The manufacturing process of mass-produced electronics involves toxic materials and a large amount of energy.

More specifically, the steel manufacturing for the laminations in the motor is an involved process. Steel is a material that consists of iron with most of the carbon removed, and 98% of mined iron from the Earth's crust is used to make steel. To convert iron ore to steel various polluting furnaces must be used, which consume large amounts of energy to reach required temperatures. Average energy used to produce one ton of steel is 18.68 GJ, and this also releases 1.77 tons of CO₂ [26]. Fifty percent of the 18.68 GJ/t required is produced by carbon-emitting coal burning [26].

These motors can be used for electric vehicle design, potentially reducing CO₂ emissions, but they would also increase the use of lithium-ion batteries. These batteries may reduce greenhouse gasses if incorporated into the transportation fleet, but they are rarely recycled and their electrochemical components are not renewable resources [27]. Alternatively, the low maintenance of BLDC could increase the longevity of cars on the road, but would also diminish employment opportunities in the realm of ongoing system service. Since BLDC motors are also quieter, they could help decrease noise pollution.

Sustainability

The motor should last for a long time, but when it does reach the end of its lifecycle due to grit in the bearing or mechanical wear the PCB will need to be disposed of with special care due to its lead content. The EPA and Virginia Waste Management Board regulate the disposal of hazardous waste and recommend that PCBs are recycled in a proper facility [28]. The addition of a voltage regulator and heat sinks on the PCB will increase the longevity of the board by restricting abnormalities on the power supplies [28].

Additionally, when choosing steel vendors, it would be more sustainable to use recycled steel in the production of the laminations. This will allow for a longer life of the iron ore mined in the manufacturing process [26]. In the future, expanded functionality of this teaching motor could be achieved by adding programming for the extra hardware button or the SPI port. By routing options on the PCB for future works, one motor can be used to teach multiple electromagnetic concepts. This multifunctionality would require fewer pieces of equipment in lab, saving space, time, and money.

Health and Safety

High voltages are present and should be handled safely, even with the addition of the voltage regulator and heat sinks on the PCB. Additionally, the general moving nature of a motor needs to be safely enclosed to avoid physical contact. The plexiglass mounted above and below the motor offers some degree of protection without obscuring the view of the internal movements of the rotor. The lateral sides of the motor are open which offers a better view of the motor, but also increases risk of injury if something were to get lodged into the motor.

Manufacturability

This system will be fairly easy to replicate. Most components could be assembled by machine, however, for this senior project the windings were done meticulously by hand. For mass production a pre-made motor could be used to make production more efficient, but would also take jobs of employed human motor winders. The PCB components were common and fairly inexpensive, and the price would further decrease with bulk orders of the system.

This project used soldering, winding, and steel manufacturing skills. Since the board contains both surface and through hole components, the calibration of large-scale soldering would have to be very precise. Automated programming of the microcontroller could be reached fairly easily. The cutting of the steel laminations would have to have greater tolerance for expansion of gaps between the laminations, with potential modifications to the bobbin dimensions, required magnetic wire length, and outer diameter of the rotor. The use of a stamp press would greatly reduce variations across large samples of stamped laminations.

Ethical Issues

A college education is required for someone to earn an engineering degree. However, college is a costly endeavor, and college enrollments disproportionately reflect the broad socioeconomic breakdown of the United States. Restricting the instruction of electromagnetism to the college level means that the teaching tool developed in this capstone project would not reach a very socioeconomically diverse set of students.

Intellectual Property Issues

Below are three patents with similar technology to the proposed design of a BLDC motor for in-class demonstration. While all of these motors are for instructional purposes, none of them include the plexiglass mounts incorporated. Additionally, none of them included serial ports for future expansion of embedded programming. There were also patents for the simulation software packets of BLDC motors. No patents combined the option of firmware expansion and also included clear visibility of the motor's operation.

The first patent [29] proposes a patent for an "Educational device for teaching electric motor or generator principles". The presented technology is classified as "Models for scientific, medical, or mathematical purposes, e.g. full-sized devices for demonstration purposes for physics for electricity or magnetism for motors; for generators; for power supplies; for power distribution". This patent's main claim is to have multifunctioning mechanical parts to easily demonstrate a series of electrical and magnetic principles. This includes retractable magnets, removeable armature pieces, and U coils on the outer radius for transformer demonstration. In light of these claims, the capstone project presented is still patentable, because the Watts Our Capstone's developed system relies on electronic commutation that this motor does not require.

The alternate independent claims focus on different subsystems, like the mechanically interchangeable parts and layout of the pieces [29].

The second patent [30] proposes a patent for "Brushless direct current motor demonstration model". The presented technology encompasses an aluminum hull rotor, stator, power coil, bulb, sensor, controller, 12V battery, and power switch. This patent's main claim is to demonstrate a brushless DC motor with a stator circumventing the rotor. This includes a generic switch and controller. This patent was not detailed enough to render this project unpatentable. The capstone project presented is still patentable because Watts Our Capstone's developed system includes the design of the controller system, the future hardware programming, and the asymmetric motor design [30].

The third patent [31] proposes a patent for a "Multi-winding brushless motor teaching training device". The presented technology encompasses a type of engine that uses multiple windings that is simple in structure, low cost, and demonstrates how a brushless engine works. This patent's main claim is a plated engine that can be provided load onto the grouped coils. This includes windings, iron core, driving wheel, belt gears, shaft and bearings, series rectifier circuit, power loop of load, voltage table, and binding paneling [31].

In light of the claims made in the aforementioned patents, the capstone project presented is still patentable, because Watts Our Capstone's developed system relies on varied voltage commutation, a constant current of one Amp, the option of hardware and firmware customization, and electric feedback from the mechanical system.

Detailed Technical Description of Project

The goal of this capstone project was to build a brushless DC motor to be used in the Electromagnetic Power lab at the University of Virginia. The user, a student in the power lab, was to control the motor parameters and watch the relevant parameters of the motor change in front of them. This project encompassed the design of a brushless DC motor, speed controller, and hardware interface to control the motor and display relevant values.

The construction of the motor involved the design of the motor body/windings, a PCB to drive the motor and support a hardware user interface with an OLED display, and embedded programming to control motor speed from the hardware interface. The system was powered by a 24 Volt, 1 Amp supply, which was connected via a voltage regulator to the microcontroller in order to output 6 signals that controlled the driver circuitry. This driver circuitry utilized three half bridge drivers that were then used to deliver 24 V to the 3 phases of the motor.

When a coil is turned on, a magnetic field is induced. This field was produced by the windings to pull the magnets on the rotor resulting in a generated rotation. Hall Effect sensors tracked the position of the rotor by sensing the magnetic fields, which then triggered state changes in the driver circuitry via the microcontroller. A hardware interface with an OLED was connected to the PCB and microcontroller, allowing signals fed to the microcontroller from the motor to be displayed. Additionally, buttons on the hardware interface allowed the user to control the motor RPM by sending signals to the MSP and the PCB.

The entire system was broken down into the following subsystems:

- Hardware
 - i. Power supplies
 - ii. Schematics
 - a) Main PCB
 - b) Hall Effect Sensor PCB
 - iii. PCB Design
 - a) Main PCB
 - b) Hall Effect Sensor PCB
- Firmware for the Speed Controller
 - i. General
 - a) Timing implementation for speed control of 3-phase
 - b) Debounce and interrupt procedures
 - c) Hall Effect logic reading
 - RPM speed determination
 - State declaration
- Mechanical System for the Motor
 - i. Stator
 - a) Windings
 - b) Bobbin
 - ii. Rotor
 - a) Shaft, bearings, and casing
 - b) Magnets
 - iii. Plexiglass mount for Main PCB, Hall Effect PCB, and motor

A high-level block diagram for the overall system is shown below in Figure 1.

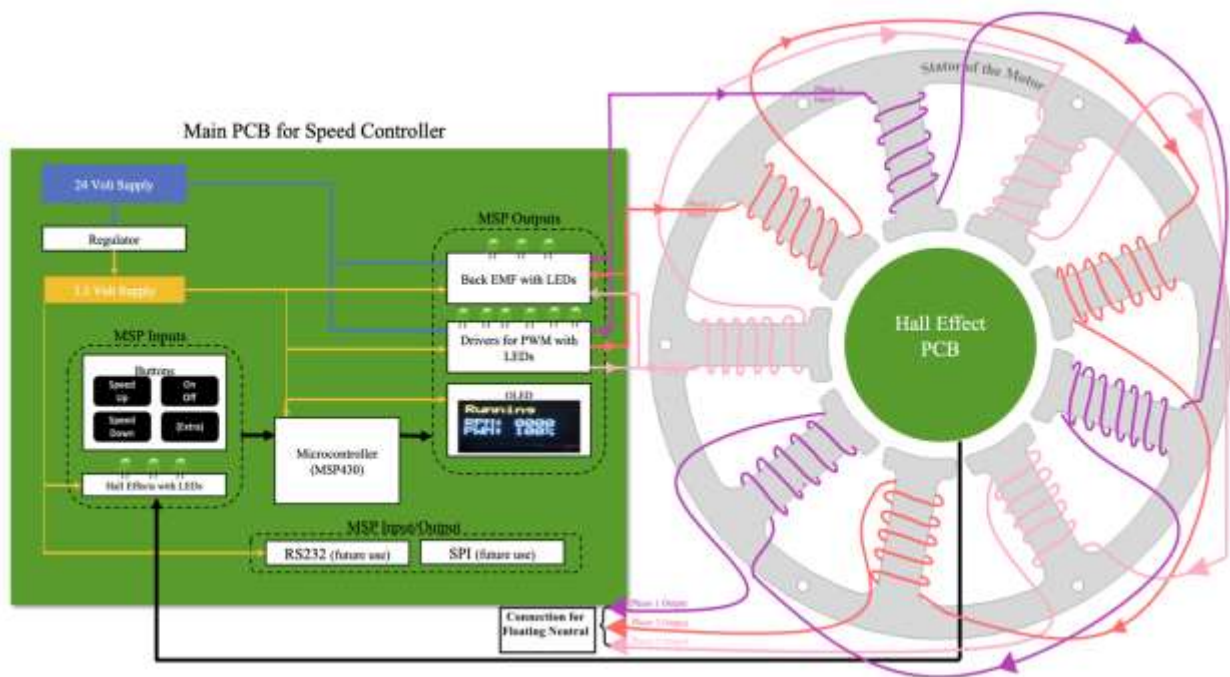


Figure 1. High Level Overall Block Diagram

A more detailed diagram is shown below in Figure 2 to demonstrate how the designed microcontroller connections were planned based on the desired overall function. Figures 1 and 2 combined helped determine the circuit schematics and PCB layout.

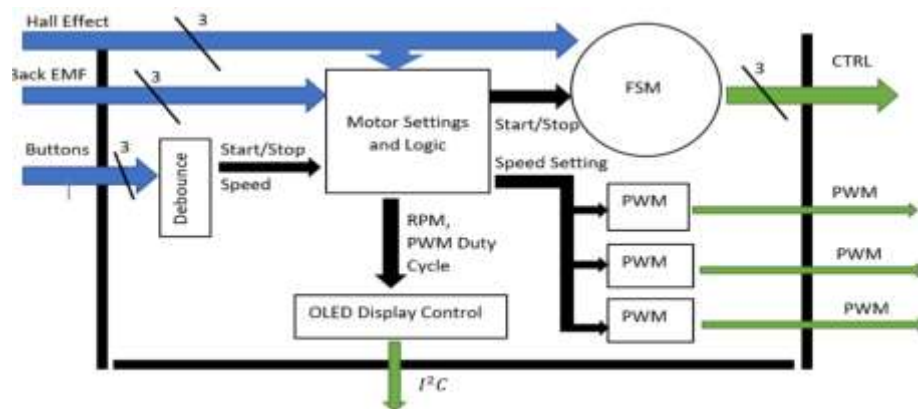


Figure 2. High Level Embedded Plan Block Diagram

Hardware

The hardware consisted of two PCBs, one for the main speed controller and one for the hall effect sensors to read the mechanical position of the rotor magnets. As shown in Figure 1, the main PCB was powered from the 24 Volt - 1 Amp supply and contained the MSP430 microcontroller, button inputs, the hall effect sensor inputs, a voltage regulator, back EMF output, driver circuitry for the output to the motor coils, and OLED output. The second PCB was used to connect the hall effect sensors from under the rotor to the main PCB; this made the mounting of the three sensors possible without individual mounts.

Main PCB for Speed Controller

Design Decisions

The main requirements for the speed controller to function properly are as follows:

1. Create three PWM signals to induce a magnetic field in the three phase windings on the motor
2. Have an interface method to change the duty cycle of the PWM signals
3. Connect mechanical feedback from the motor to the state machine of the PWM

To better explain concepts of electromagnetism to students, design decisions were made to expand upon the basic functionality of an electronic speed controller (ESC). More specifically, selected Maxwell equations demonstrated electromagnetic relationships. The PCB's size was fairly flexible, but the layout was important to make the operation as intuitive as possible to students.

The power supplies were regulated first, stepping the voltage down from 24 volts to 3.3 volts in order to safely power the smaller subsystems on the board. Running two voltages on the board allowed an all in one approach to the supplies, as the coils and certain components also required the higher 24 volts too. For the user's PWM input to the microcontroller, buttons were used to control the motor, and turn its angular speed in rotations per minute (RPM) up or down. There was also an extra button built in with hopes of implementing a reverse rotation function.

The drivers were added to this PCB to control which coil phases were pushing and pulling the motor based on the physical position of the motor. Predesigned chips were selected that offered high and low states in order to make the implementation simpler. Additional LEDs were added to the high and low states to demonstrate which coils were activated at the same time to move the rotor. The currents introduced to the coils are the source of the driving EMF in the system, demonstrating the electromagnetic concept known as Faraday's Law of Induction [32]. Under this law, any change in the magnetic environment of a coil of wire results in a voltage (EMF) to be induced in the coil, regardless of the source of that change. It is the basis for the definition of inductance: "a property of an electric circuit by which an electromotive force is induced in it by a variation of current either in the circuit itself or in a neighboring circuit; equal to the ratio of the induced electromotive force to the rate of change of the inducing current" [32, 33]. As observed in the equation below, the EMF voltage also changes based on the number of coil windings, and will change based on the combination of stator slots and magnets [1].

$$\text{Faraday's Law: } EMF = -N \frac{d\Phi}{dt}$$

Another addition to the board was the back EMF circuitry and LED output. The back EMF is the result of Lenz's law of electromagnetics, which states that the EMF opposes any change so that the input EMF that is powering the motor will be opposed by the motor's self-generated EMF (also known as the back EMF) [32]. Back EMF is the generator output of the motor's rotation, and is consequently proportional to the angular velocity. As the motor speeds up, the back EMF grows and opposes the driving EMF in the coils, thus reducing the amount of voltage across the coils [32]. By adding this element to the PCB students are exposed to two concepts of electromagnetism: Faraday's Law and Lenz's Law [34].

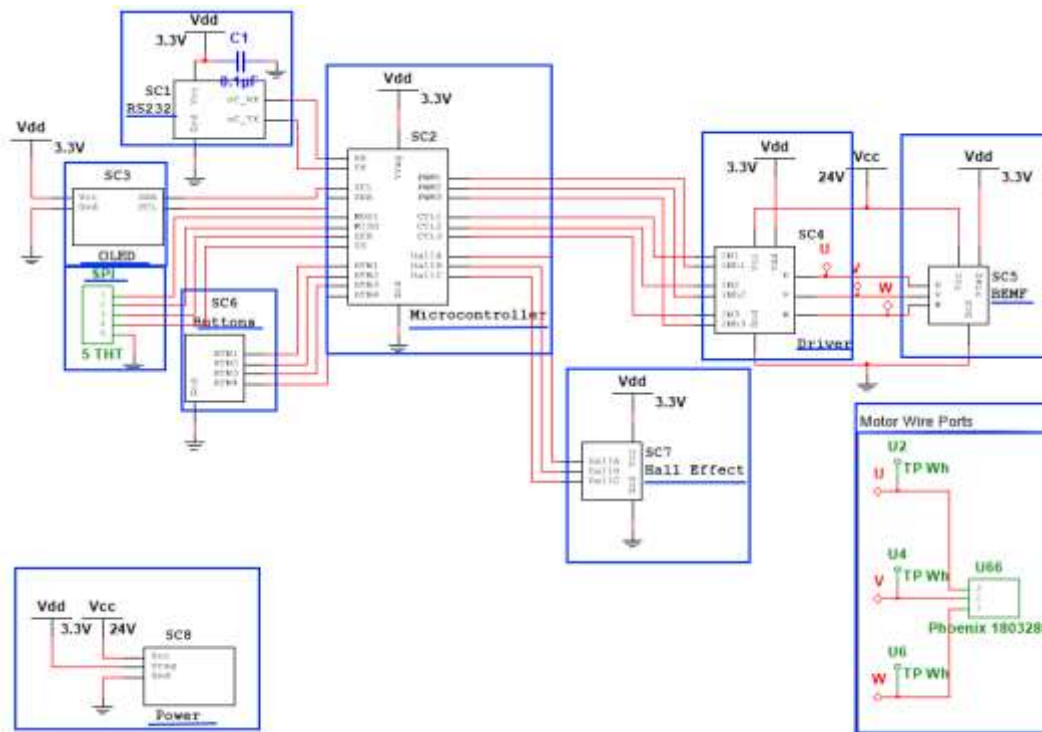


Figure 3. Main PCB Schematic

The overall system schematic is shown above in Figure 3 for the main PCB speed controller. Industrial common components used consistently throughout the subsystems included LEDs, standard test points, resistors, capacitors, and .1" male headers. Based on the design decisions and expansions explained in the previous section, the schematics were broken down into the hierarchical blocks for each subsystem.

1. *Power Supply* - In order to step the DC voltage from 24 V to 3.3 V, a voltage regulator was used [35] Banana jack connectors [36] were used to power the board and motor from the 24 V supply from UVA's power lab benches. Strong decoupling capacitors were used between the supply inputs to ensure that no AC signals would corrupt functionality of the motor.

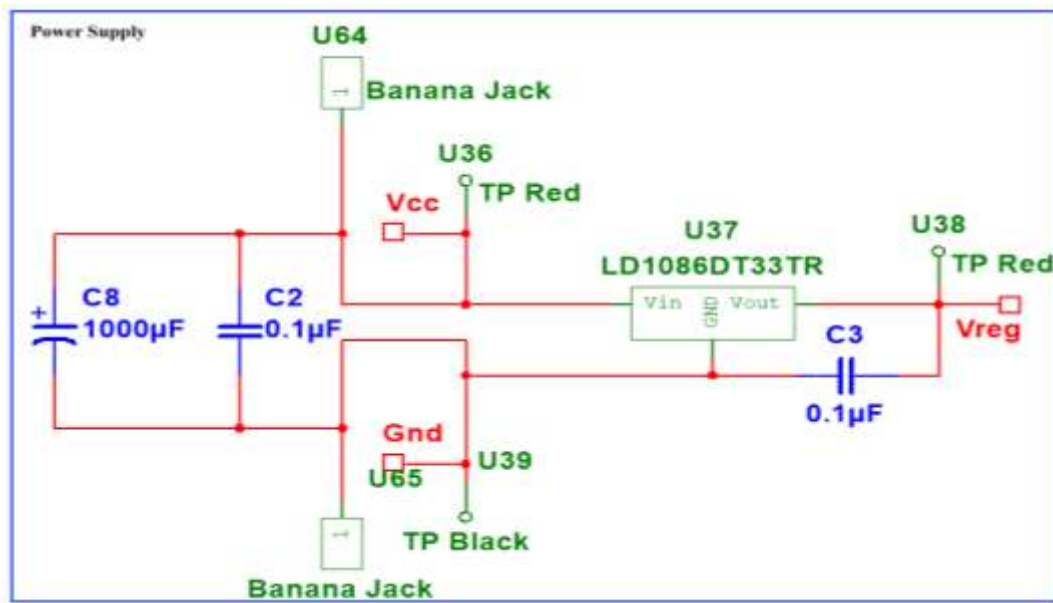


Figure 4. Power Supply Schematic

2. *Buttons* - The button circuitry was very simple, consisting of 4 switches [37] to control the power status, speed up, speed down, and the auxiliary button for future work. Various interrupts were written in C programming to handle button presses.

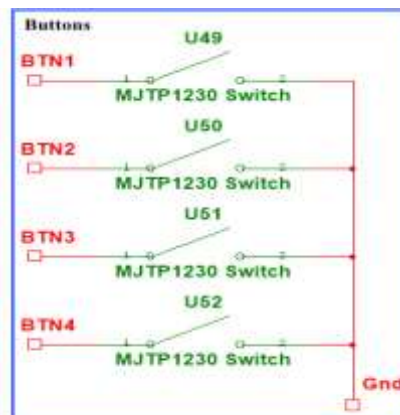


Figure 5. Buttons Schematic

3. *Drivers* - The drivers were used to commute through the speed controller's FSM [38]. The driven voltages ultimately moved the rotor about the shaft. Logic connected LEDs [39,40], with current limiting resistors, were broken out to display whether each coil was activated and whether it was being driven high or low in order to push or pull the magnets around. Other resistors were connected to the chips in accordance with the data sheet. 7k resistors were used to buffer too much current from going into driver chips. The 1k and .51 k set the current sensing and slew rate for the driver. The 1k and .51 k set the current sensing and slew rate for the driver.

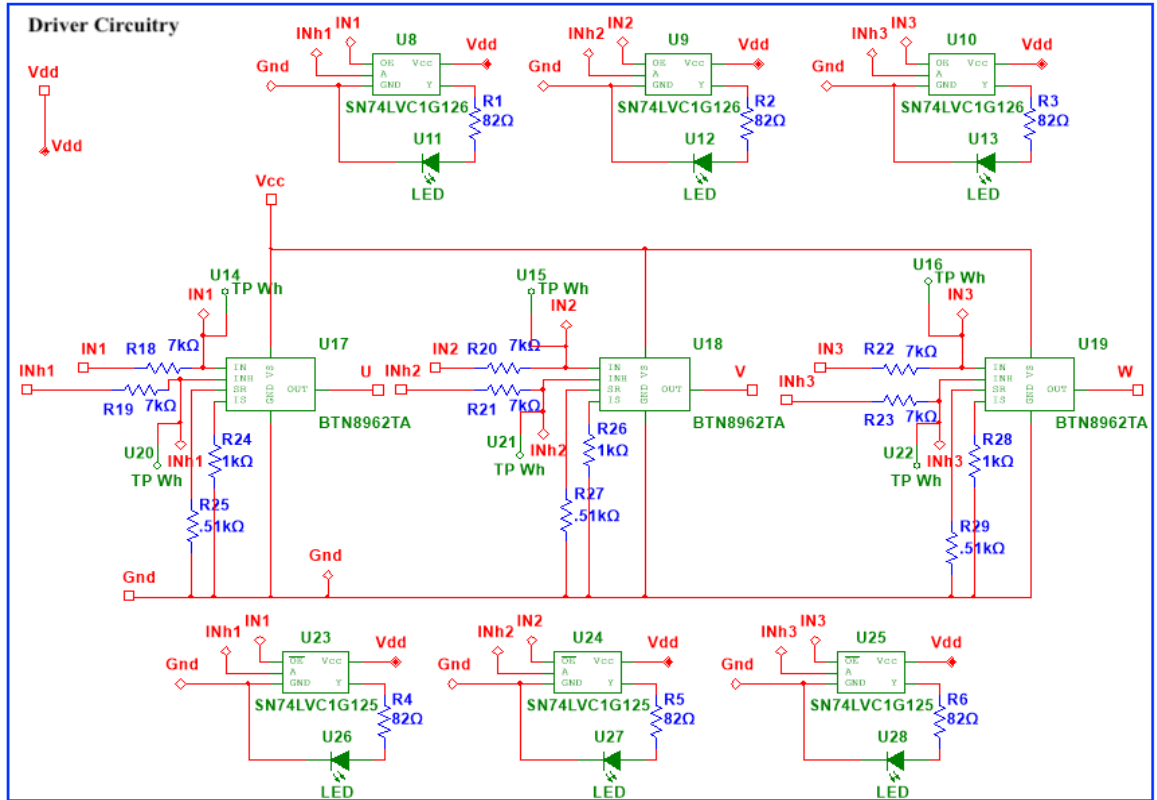


Figure 6. Driver Circuitry Schematic

4. *OLED* - The OLED and breakout board [14] displayed the motors current configuration including the FSM status and the speed in RPM. The 4.7k resistors were used in accordance with the I²C standard [15] to provide the pull-up voltages on the signal lines.

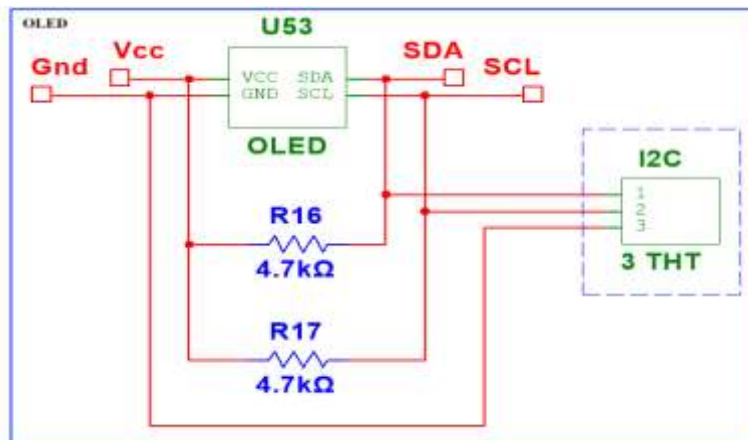


Figure 7. OLED Schematic

5. *Hall Effect Sensor Connections* - The Hall Effect sensor logic was added to the main PCB with LED output. This allowed students to read the three mechanical feedback lines from the PCB mounted under the rotor. This feedback was also fed to the microcontroller to iterate through the FSM [41,42].

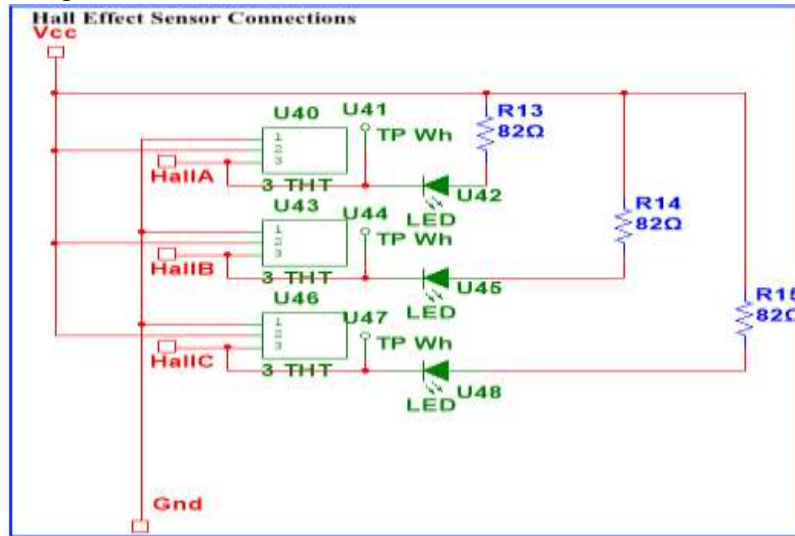


Figure 8. Hall Effect Sensor Connections Schematic

6. *Back EMF* - The induced opposing back EMF on the floating coil was displayed to help introduce the concept to students, as explained in the introduction of this report. In order to read the back EMF a resistor was attached in parallel to each phase coil; this established a virtual ground where all the phases met. Due to the implemented voltage divider, the voltage was designed to read half of the supplied DC voltage. Each phase

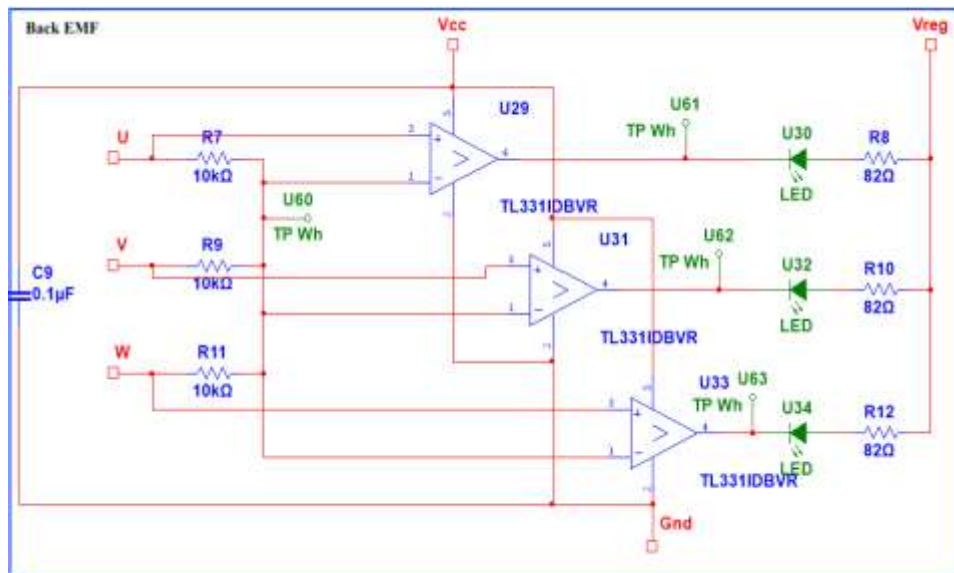


Figure 9. Back EMF Schematic

was then compared to virtual ground in order to read a high or low voltage [43]. The third "floating" coil contained the induced voltage, which ultimately resembled a trapezoidal

function [1]. This was done in hardware because the back EMF was induced during the neutral transition of the FSM while the actual flux was changing.

7. *Microcontroller* - The microcontroller was the brain of the speed controller [4]. It interacted with the various subsystems on the PCB as well as the composed code. This set the PWM voltages on the coils, the output to the OLED, handled the user's input, and enabled various hardware communications.

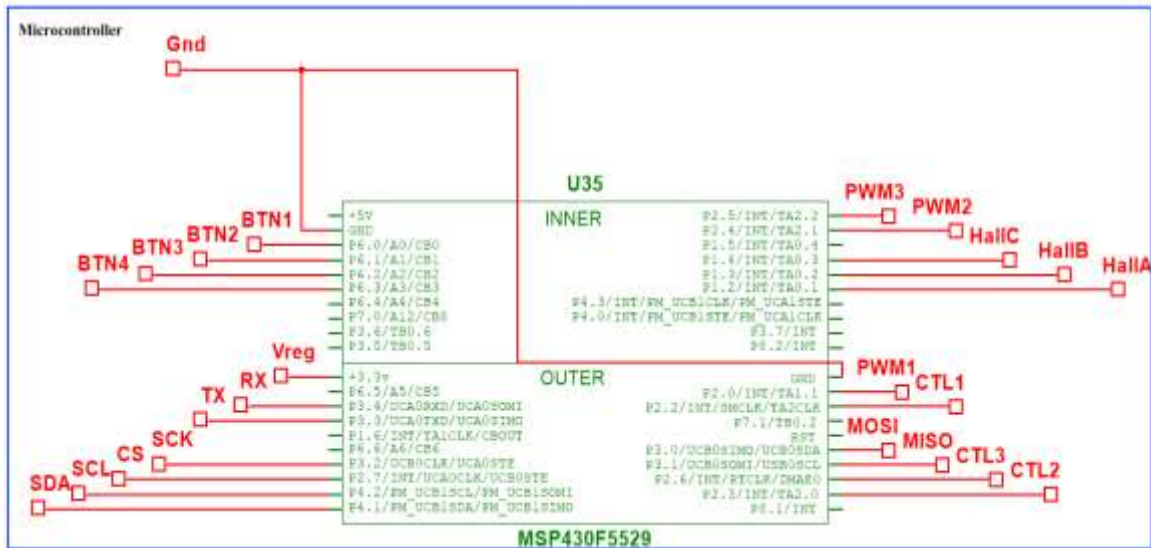


Figure 10. Microcontroller Schematic

8. *RS232 for Future Work* - Breaking this out not only allows for future expansion on the device's capabilities, but also aided in the testing of the motor's speed calculation [44,45].

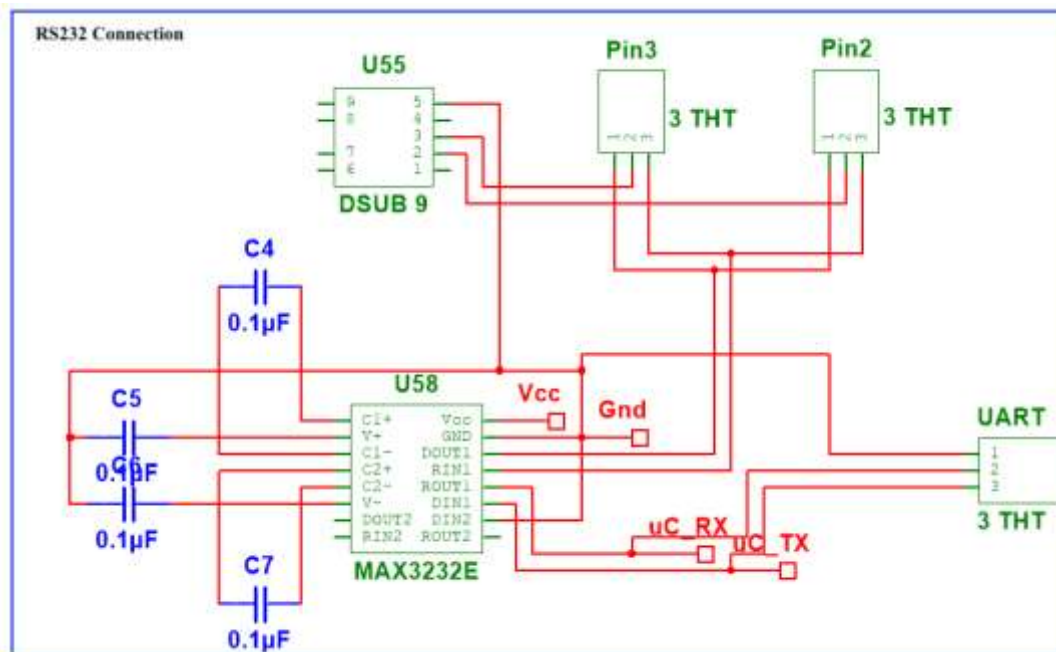


Figure 11. RS232 Connection Schematic

9. *SPI for Future Work* - The SPI header is an industry standard part that was just built out with connections for the microcontroller. There was no power required to break out the MISO, MOSI, SCK, and CS pins for expansion capabilities, but the footprint for the port was included in the main PCB diagram in Figure 3.

PCB Design

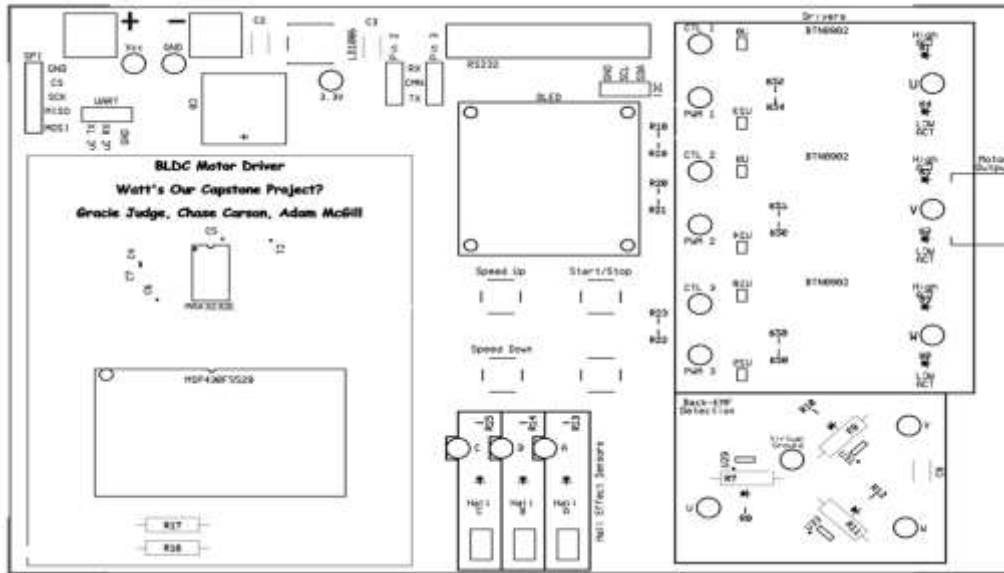


Figure 12. Main PCB Outline

The Main PCB and Hall Effect PCBs were developed in NI Ultiboard using a two-layer FR4 board. The top layer contained a copper top where the majority of traces were placed. The bottom layer contained a ground plane and a few secondary traces that did not fit on the top. The thickness was set to a standard thickness of 68 mil in adherence with Advanced Circuits' deal for students. The footprint from the PCB was then exported as a CAD file to incorporate into the 3D drawings of the mechanical system.

The basic board with only the top silkscreen is shown above in Figure 12. The traces were added to the various components mostly on the copper top. However, three driver components had to be routed on the bottom in order to achieve the required trace width, while also avoiding overlapping interferences. The board with top and bottom layers is shown in Figure 13 below, and the physical rendering is shown in the following Figure 14.

The physical layout of the board was representative of the macro system in terms of layout. From the PCB to the Plexiglass mounts the electrical connections mimic the physical layout of the system to help students visualize the flow of current from the board, around the motor and back. For example, the power supply was placed on the upper left-hand corner of the board, and the power works from that corner to the right. The motor leads extend off the right side of the board to connect to the motor on the right side of the plexiglass. The feedback from the Hall effect sensors below the rotor electrically connected back to the main PCB on the bottom of the board. The buttons in the center of the board are indicative of controlling the entire system. The setup for that board is outlined in the following section.

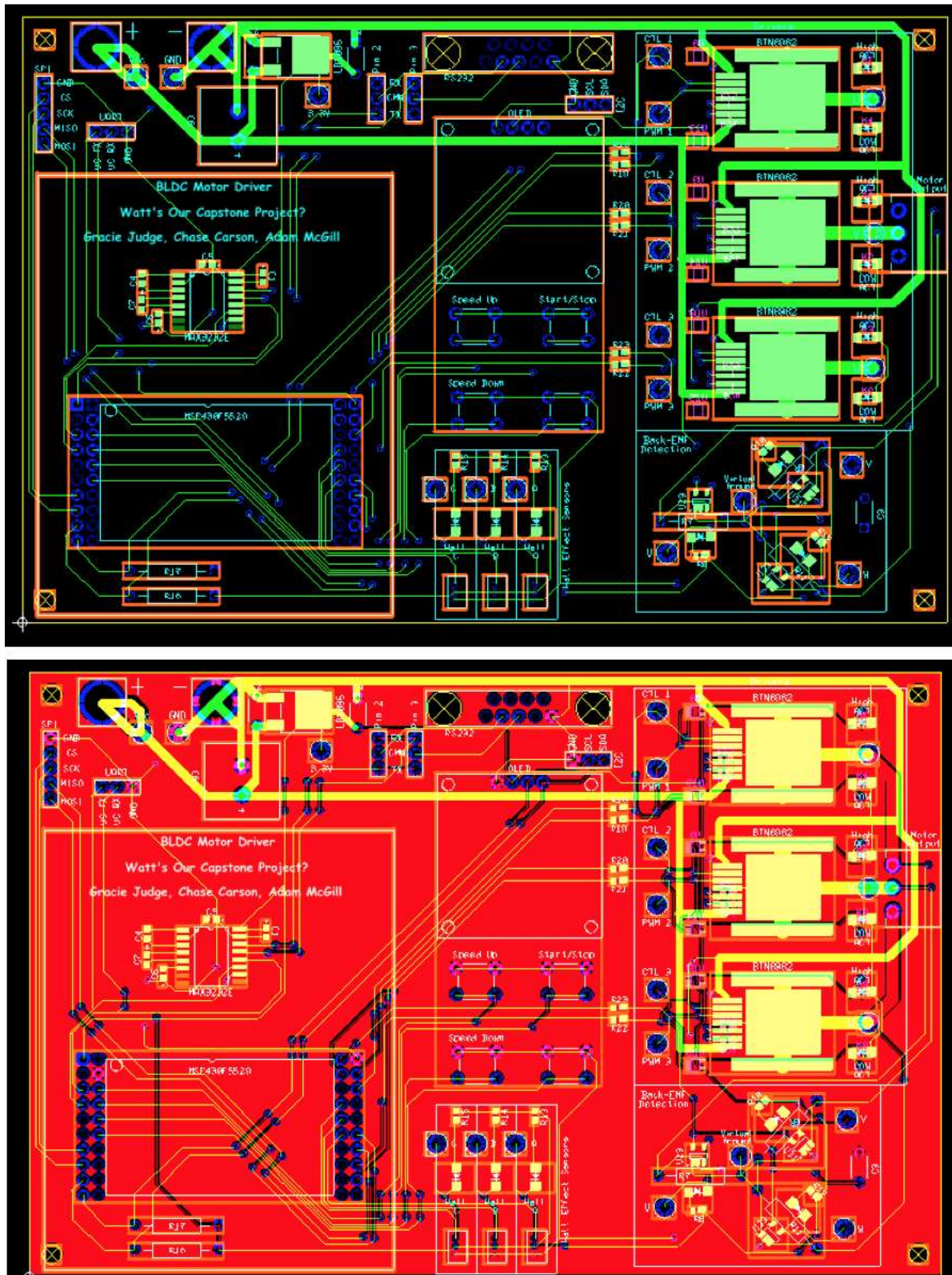


Figure 13. Main Board Layout without copper top (top), and with copper bottom (bottom)

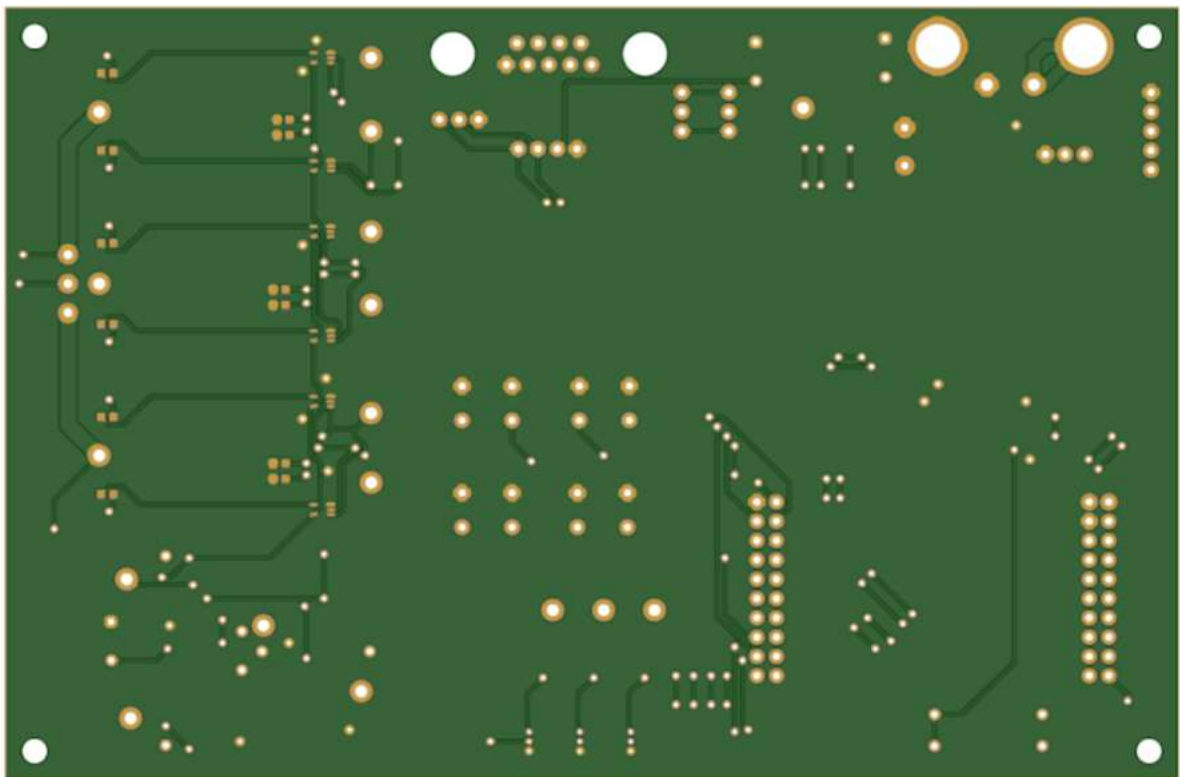
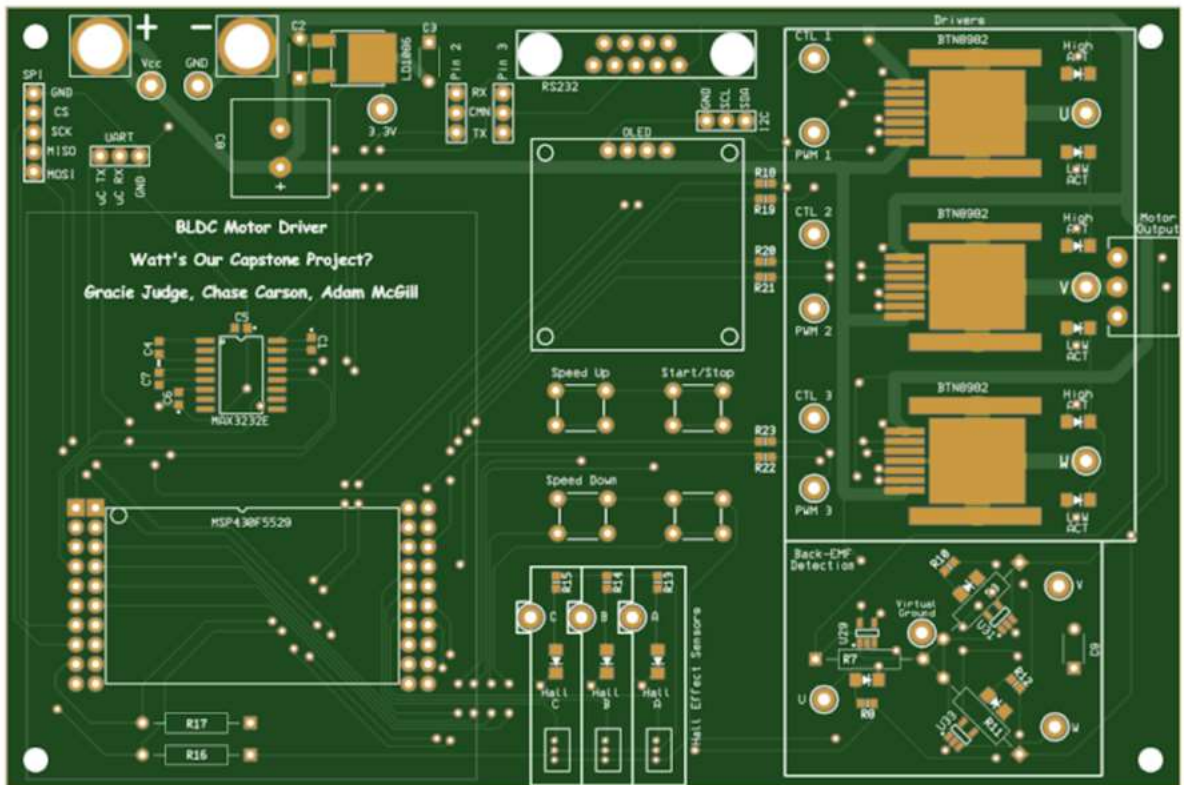


Figure 14. Main PCB's Top (top) and Bottom (bottom) Rendering

Hall Effect PCB

Design Decisions

The hall effect sensor PCB was simpler than the Main PCB because it was only used to mount the sensors beneath the spinning rotor [46]. Hall effect sensors convert magnetic signals to electrical signals that are easily read in electronic circuits. These solid-state devices are extremely useful in the applications of directional movement - in this case the angular velocity of the motor [47]. They are activated by an external magnetic field above a certain threshold. These signals from the three hall effects were jumped from the Hall Effect PCB to the Main PCB in order to encode the state machine based on the mechanical position of the rotor.

Schematics

As mentioned above, this was a fairly simple PCB design. Two threaded standoffs were soldered to the board to provide a point to mechanically attach the Hall Effect board to the entire system with screws. Additionally, decoupling capacitors were added to ensure proper function of sensors. As shown in Figure 15 below, identical supplies, sensors, and capacitors were added to each of the three phases.

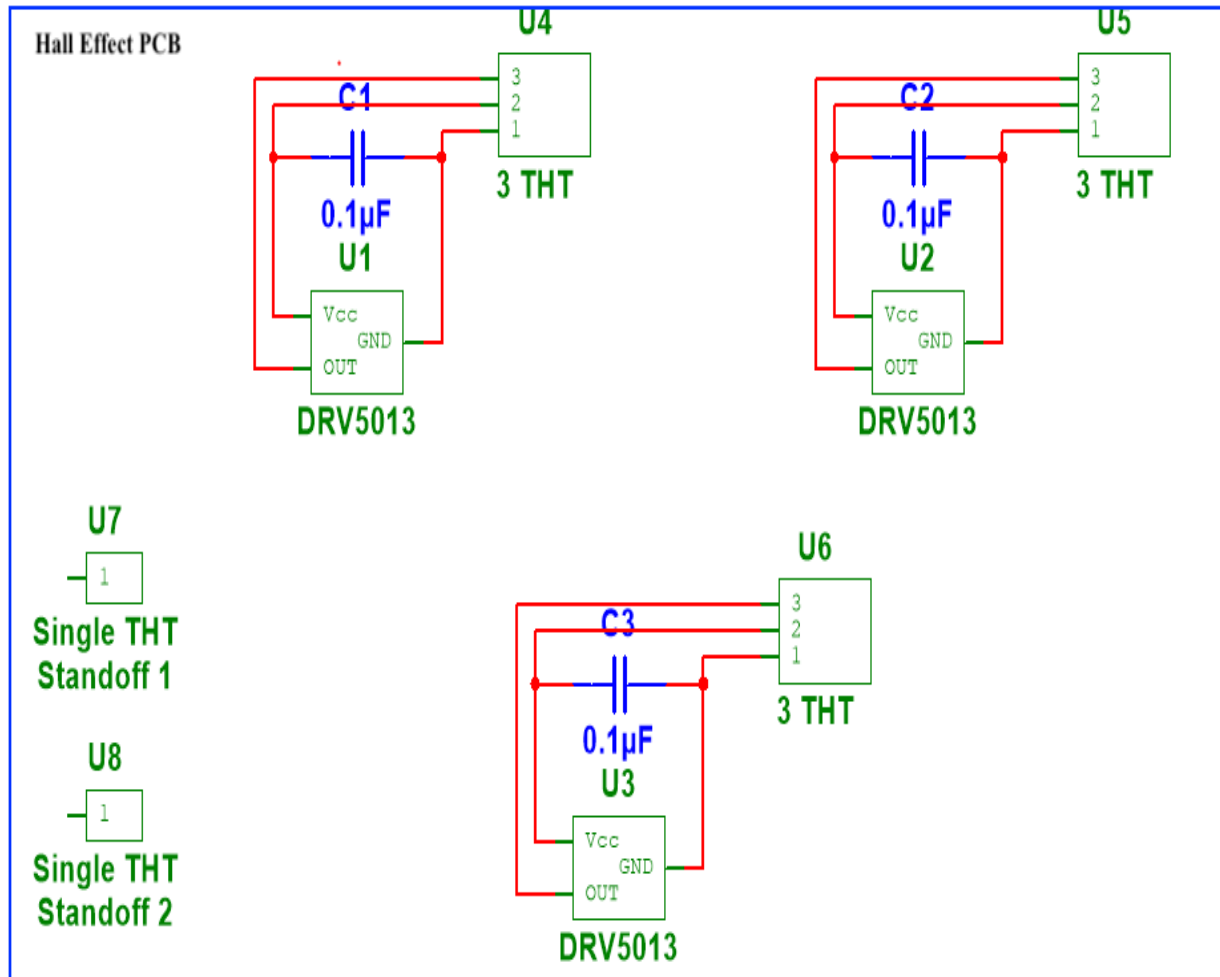


Figure 15. Overall Hall Effect PCB Schematic

PCB Design

The PCB would ideally have been fabricated as a circle to perfectly rest beneath the rotor without interference from the fields of the coils. However, Advanced Circuits' group deal to students did not include circular PCBs, so the design was made to be a square without traces in the corner. The lack of traces allowed the board to be cut to shape after it was fabricated in order to position it properly under the motor.

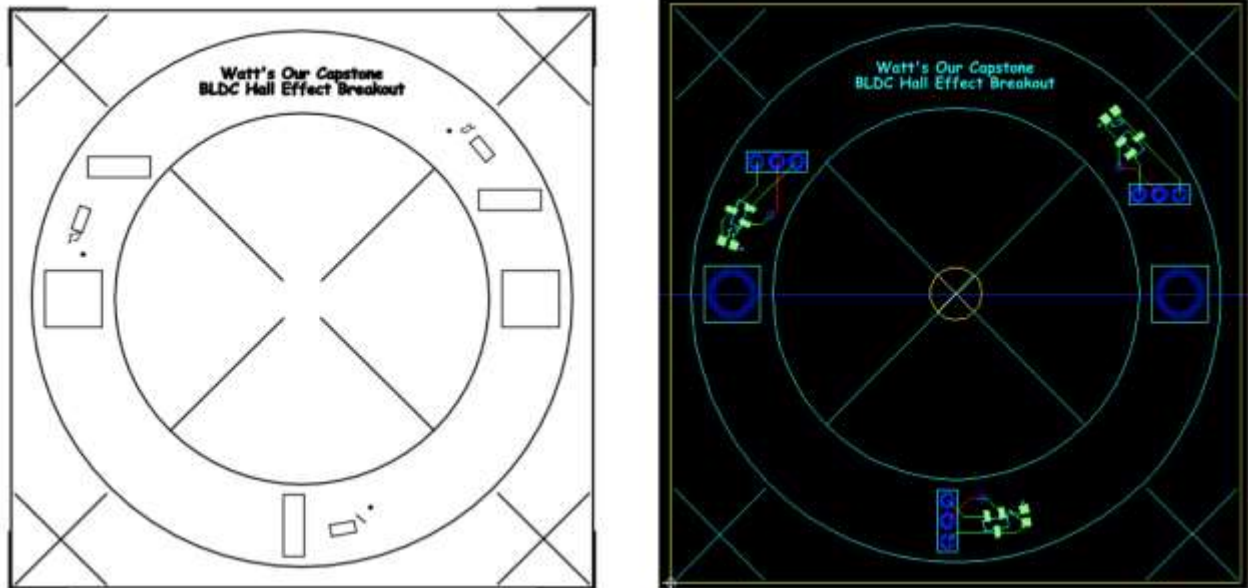


Figure 16. Hall Effect PCB Layout Outline (left) and Traces (right)

The overall layout of the board and the traces on the board are shown above in Figure 16. The tracing was very quick, and rendering of the PCB's top and bottom is shown below in Figure 17.



Figure 17. Hall Effect PCB's Top (left) and Bottom (right) Rendering

Firmware

The firmware controlled the motor drivers by decoding the mechanical state of the motor from the hall effect sensors' feedback and providing control and PWM signals based off the motor's electrical state. The motor's electrical state was tracked with a Finite State Machine (FSM), which transitioned on interrupts triggered by changes in the Hall Effect readings. Hardware buttons were used to toggle the power and speed of the motor, with the speed then outputted to the graphical OLED display. Pin breakouts for SPI and UART connections were provided for future modifications and debugging.

Button Inputs

The hardware buttons were added to the main PCB as shown in the previous section's schematics [37]. These buttons were continuously polled using C code implemented on the microcontroller. Polling was conducted via 10 millisecond timer interrupts, which decided when to react to the button presses. Interrupt service routines (ISRs) were built into the timer in order to check the status of the various buttons, which ultimately simplified the debounce routine.

Hall Effect Sensors and PWM

The Hall Effect sensors were used to decipher the mechanical position of the spinning rotor magnets [46]. The rate of change in the position of the magnets determined the speed in RPM [1,48, 49]. The FSM tracked the motor state and was able to increase or decrease the speed based on button input and the duty cycle of PWM supplied to the drivers. The FSM transitioned to the next state based on the timing diagram for the nine slot eight pole BLDC commutation. The PWM voltages on the coils, which drove the rotation of the motor, were controlled using the MOSFET driver chips' configuration [38].

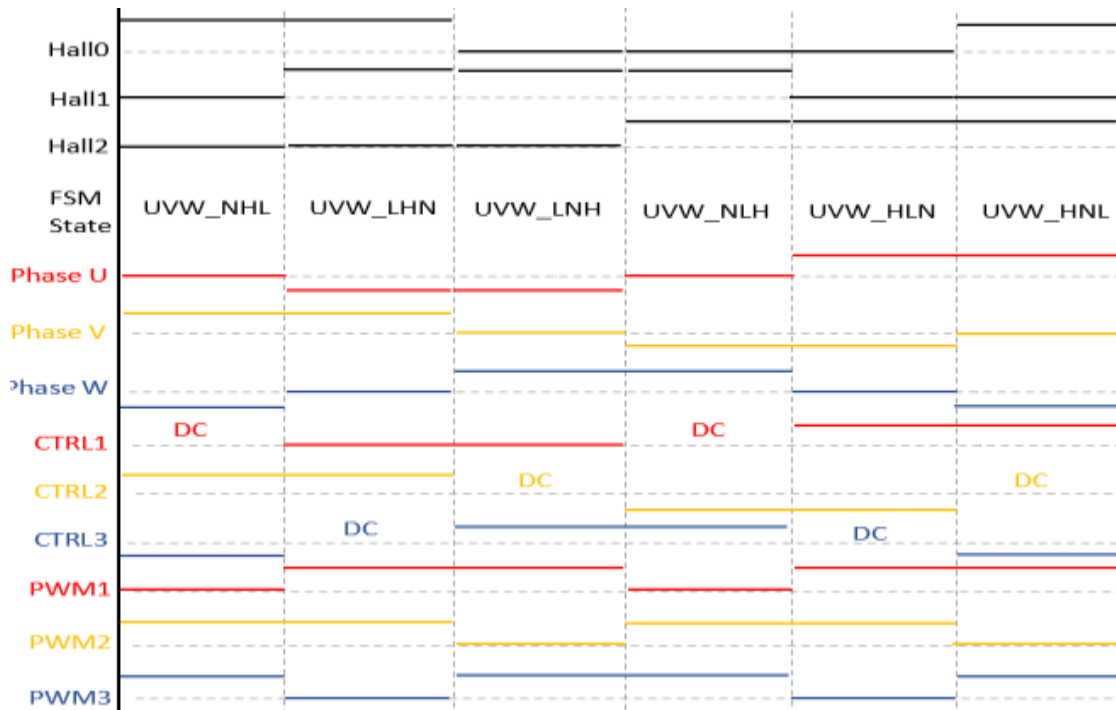


Figure 18. Timing Diagram for Drivers

OLED Display

The OLED displayed the current operation configurations for the motor. This included the location in the state machine, the RPM speed, and the PWM duty cycle. The output of the OLED is shown in the Figure 19 below.



Figure 19. Realised OLED Display

Mechanical

The mechanical system's 3D drawings were made in Autodesk Inventor. This software enabled the group to combine the designed PCBs mentioned in the Hardware section of this report with the steel motor system, plexiglass mounts, and custom plastic 3D printed parts.

The drawings of the stator and rotor were used to cut the laminations of the rotor and stator that would stack up to the desired depth of the system. With the provided laminations, it was determined that 70 laminations would be used in order to conserve a few extra sheets to test the cutting tools on. Additionally, the desired magnets were .75 inches in depth, which set the maximum length of the motor's steel configuration.

1. *Stator* - The stator was the stationary outer diameter of the motor assembly. It held the bobbins, the windings and was mounted to the plexiglass using a 3D printed holder. The bobbins were assembled in halves to slide onto the steel teeth of the stator. Once the bobbins were assembled, 100 windings were wound around each bobbin. Three phases were wound with three winding bobbins in series, thus using all nine teeth of the stator.

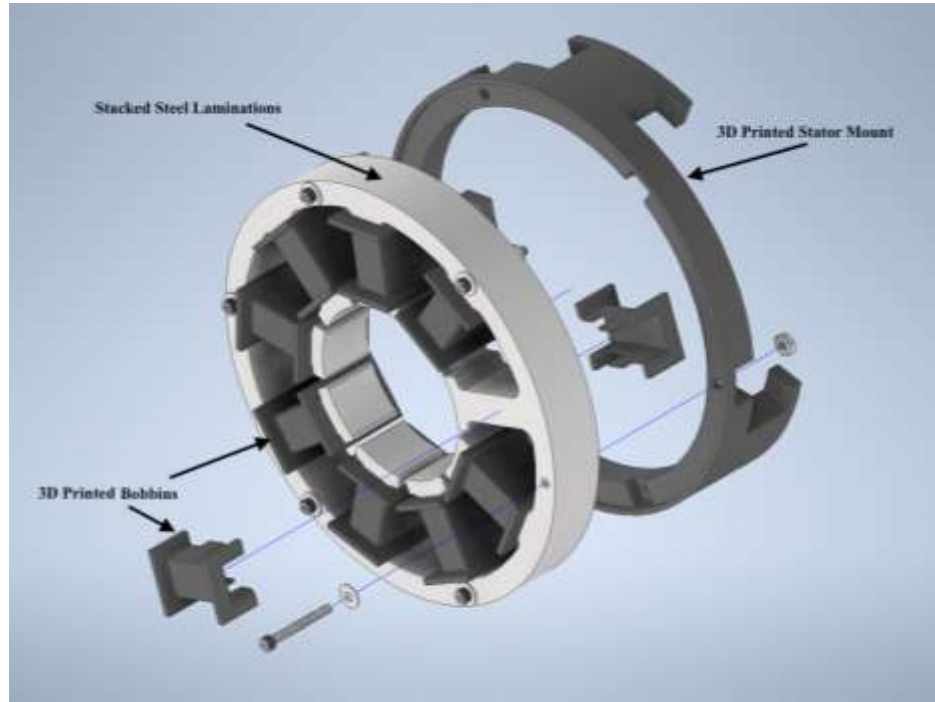


Figure 20. Stator CAD Assembly

2. *Rotor* - The rotor was the spinning part of the motor. It consisted of stacked steel laminations circumscribed by the selected magnets, which would be attracted or repelled

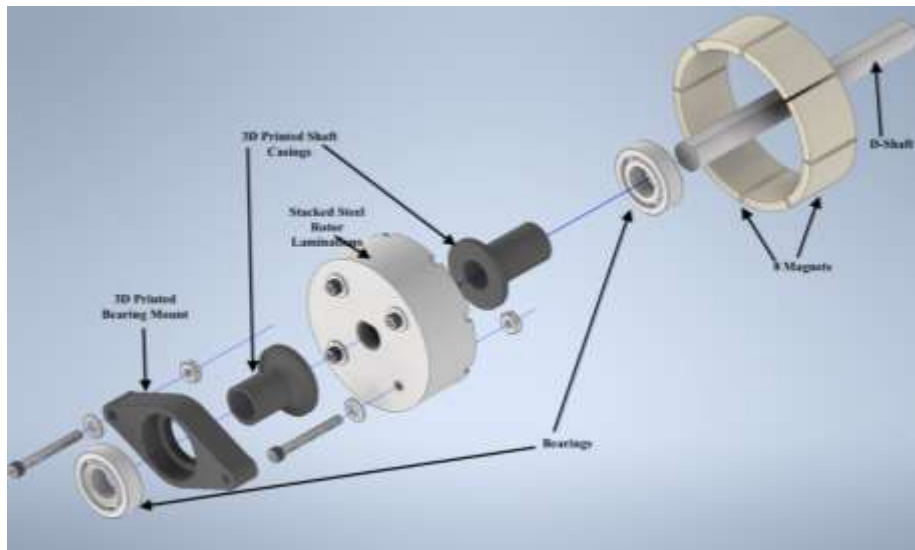


Figure 21. Rotor CAD Assembly

by activated coils on the stator. Additional casings were added to keep the shaft from wiggling inside the rotor. Another part was printed to mount the top bearing.

3. *Assembly* - The overall assembly is shown below including the plexiglass mounts, the two PCBs, and how the rotor nestles within the "hole" of the stator.

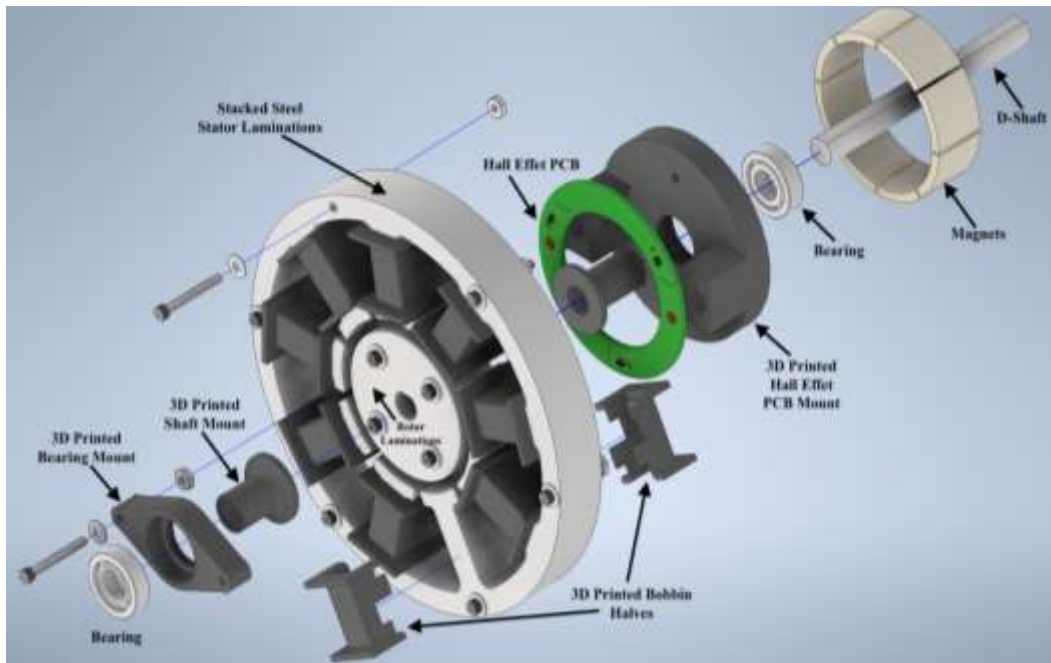


Figure 22. Motor CAD Full Assembly

The stacked view from Figure 22 above was then mounted in between two sheets of plexiglass. Plexiglass was chosen to enable the students' view of the operating motor. The main PCB containing the speed controlling microcontroller was mounted on the bottom layer of plexiglass. An extra part was 3D printed to restrict the main PCB from flexing when the buttons were pressed to power the motor or change the speed.

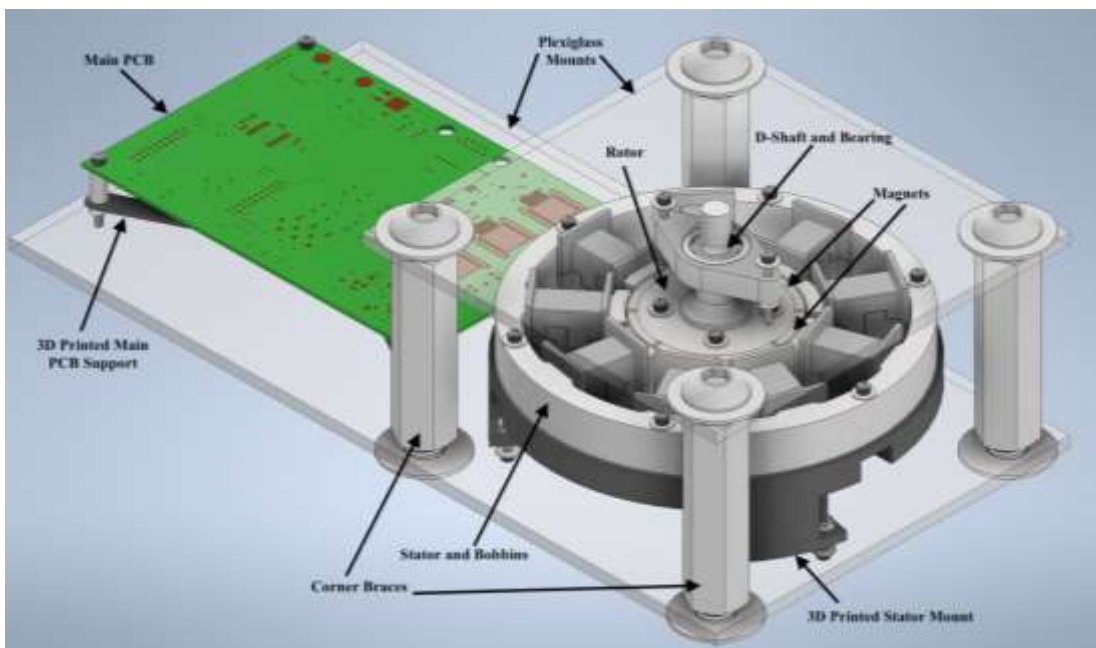


Figure 23. Entire System CAD Full Assembly

While Figures 22 and 23 above are representative of the final design, there were changes implemented when comparing this system to the originally designed one presented at the beginning of the semester. There were ultimately a few setbacks in regards to the mechanical design of the system. Originally, the steel laminations were tolerance to have an extra 25 mils for the waterjet cutting. However, the steel shifted slightly during the cutting process, which resulted in a rotor that did not fit within the inner diameter of the stator. Once the sizing was corrected using a lathe on the rotor, the magnets were also larger than expected, which led to further shaving off of the stator.

Another mechanical issue was the minor vibrations of the windings along the originally unprotected steel. The windings were found to be electrically shorted to the stator without bobbins, so 3D printed bobbins were fabricated to protect the second attempt of windings. This affected the overall depth of the windings. The windings were too close to the original hall effect mount, which was solved by making the O-shaped PCB shown in the Hall Effect Sensor PCB section of this report.

Finally, the corner braces of the originally proposed system were too thin which caused horizontal shearing of the top plexiglass layer. This meant the shaft of the rotor was tilting at an angle and causing the magnets to stick to the stator. In order to vertically straighten the shaft new hexagonal braces with thicker screws were used in the final design.

Project Timeline

For the preliminary project proposal, Excel 2016 was used to develop the project timeline in the format of a Gantt Chart. The tasks were broken down into organizational, mechanical, electrical, and software. All of these systems were done in parallel, but each team member was cognizant of the work being done in the other categories. The design of the PCBs was prioritized for the first shipment of bulk PCBs. Additionally, the mechanical processes were scheduled early, as delays

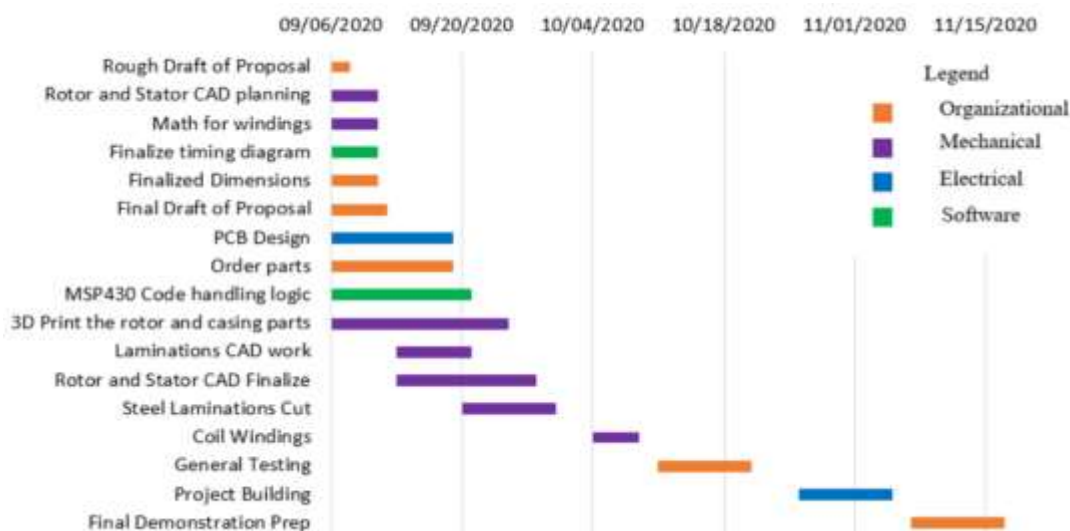


Figure 24. Originally Proposed Gantt Chart

were expected securing a steel source and manufacturing partner. The proposed timeline shown in Figure 24 was slightly modified for the midterm design review.



Figure 25. Modified Midterm Design Review Gantt Chart

By the time of the Midterm Design Review, the team realized that most tasks were taking longer due to COVID delays in the supply chain. The chart was respectively updated as shown in Figure 25 to reach the demonstration deadline of December 10th, with additional time for adequate testing. Even with a few mechanical setbacks, like having to print bobbins and rewind the motor, the deadline was met with the observed functional demo. Additionally, the breakdown of the established primary and secondary responsibilities is outlined below in Table 2.

Table 2. Team Member Responsibilities

Team Member	Primary Role	Secondary Role
Gracie Judge	Motor and PCB	CAD/Report Write Up
Chase Carson	PCB and CAD	Motor/Speed Controller
Adam McGill	Speed Controller	PCB

Test Plan

The test plan was broken into three parallel systems that were tested separately before testing the complete system. The PCB was tested to ensure the electrical points were functioning as expected with the soldered pieces. The software was tested with various "practice" cases to debug the FSM, interrupts, and voltage drivers. The motor system was tested to ensure the windings would induce mechanical motion. The test plan for the comprehensive system is laid out below in Figure 26, followed by each subsystem.

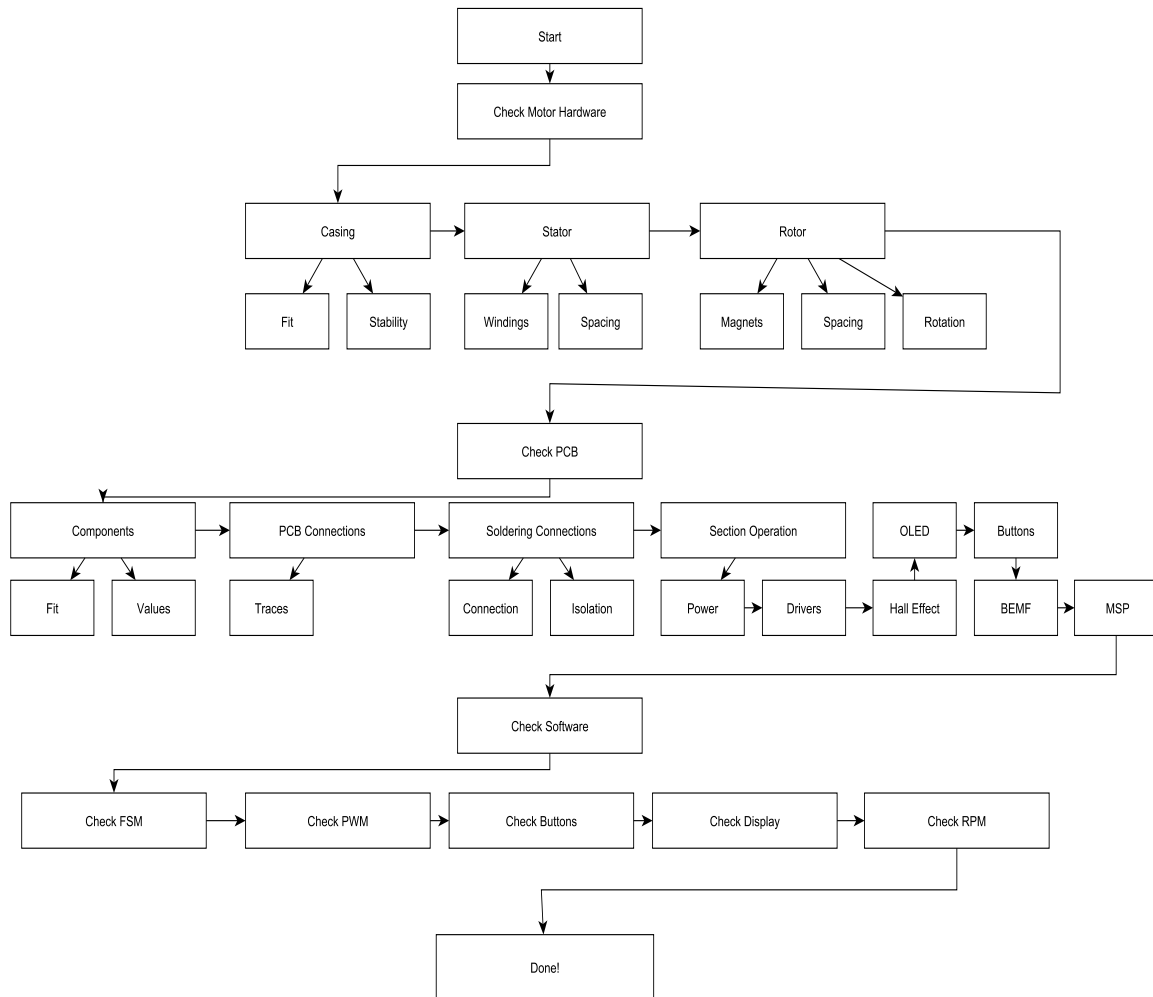


Figure 26. Entire System Test Plan

Hardware

The hardware testing protocol followed is visually demonstrated below in Figure 27.

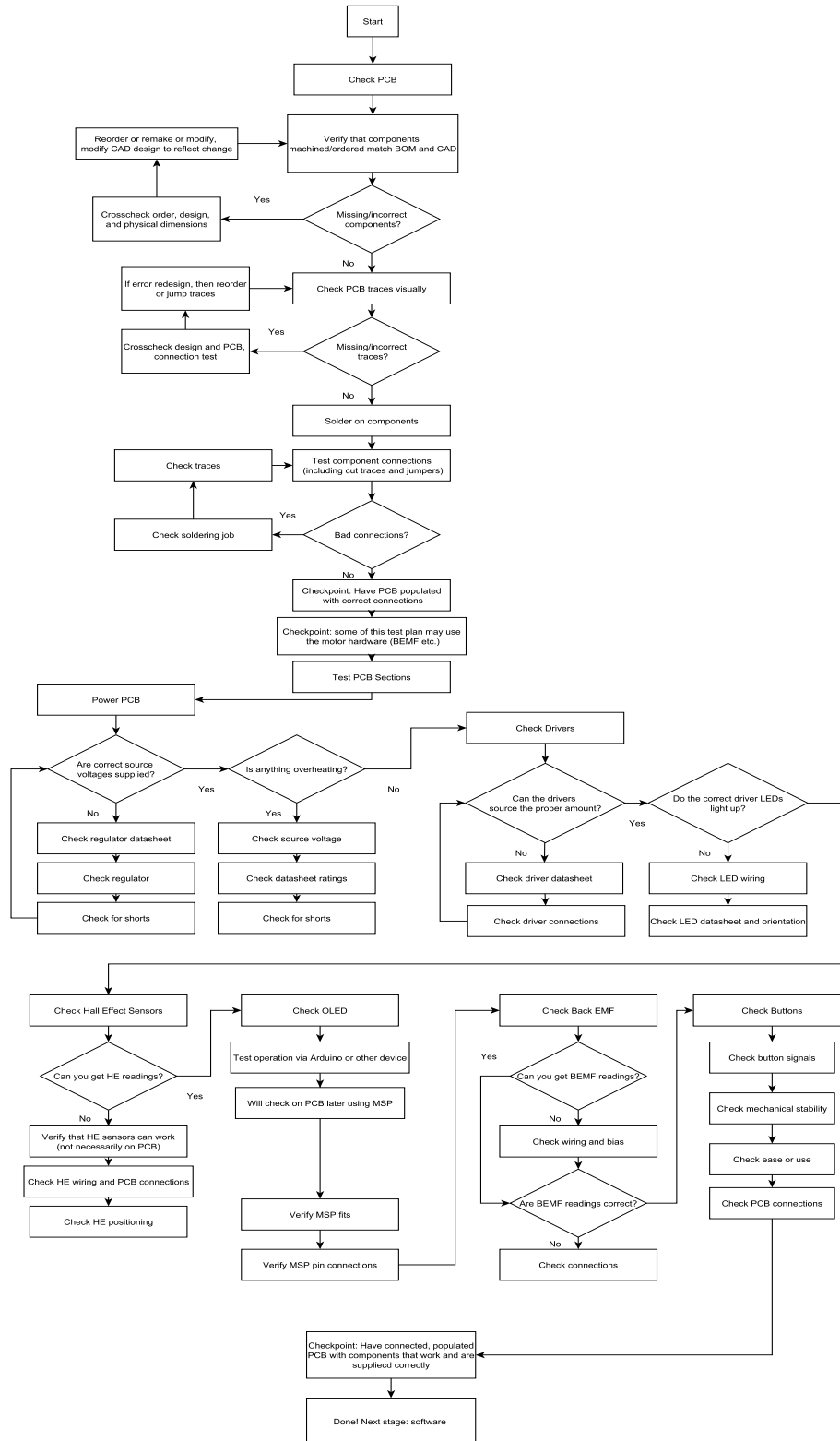


Figure 27. Hardware Test Plan

Firmware

The firmware testing protocol is visually demonstrated below in Figure 28.

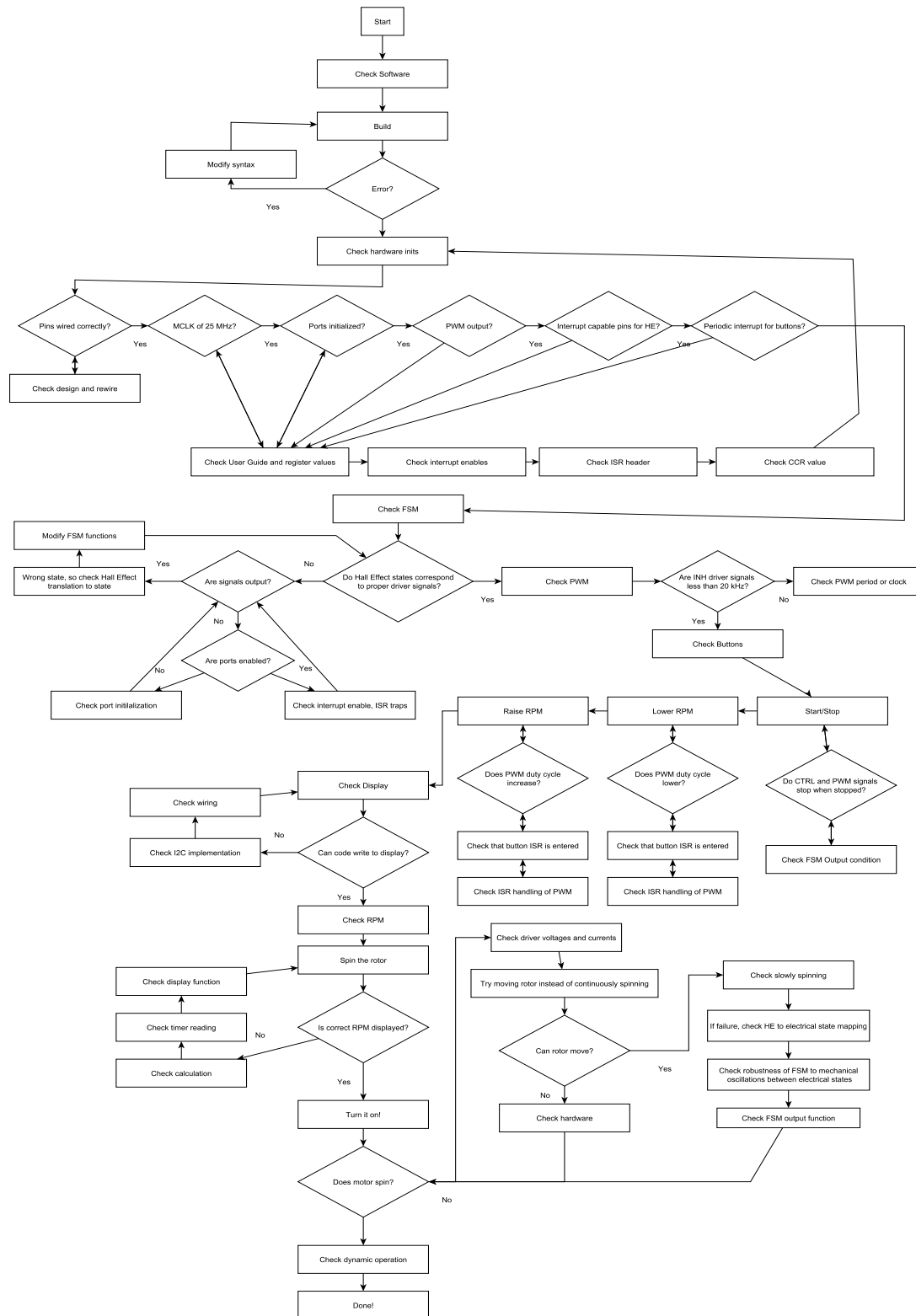


Figure 28. Firmware Test Plan

Mechanical

The mechanical system's testing protocol is visually demonstrated below in Figure 29.

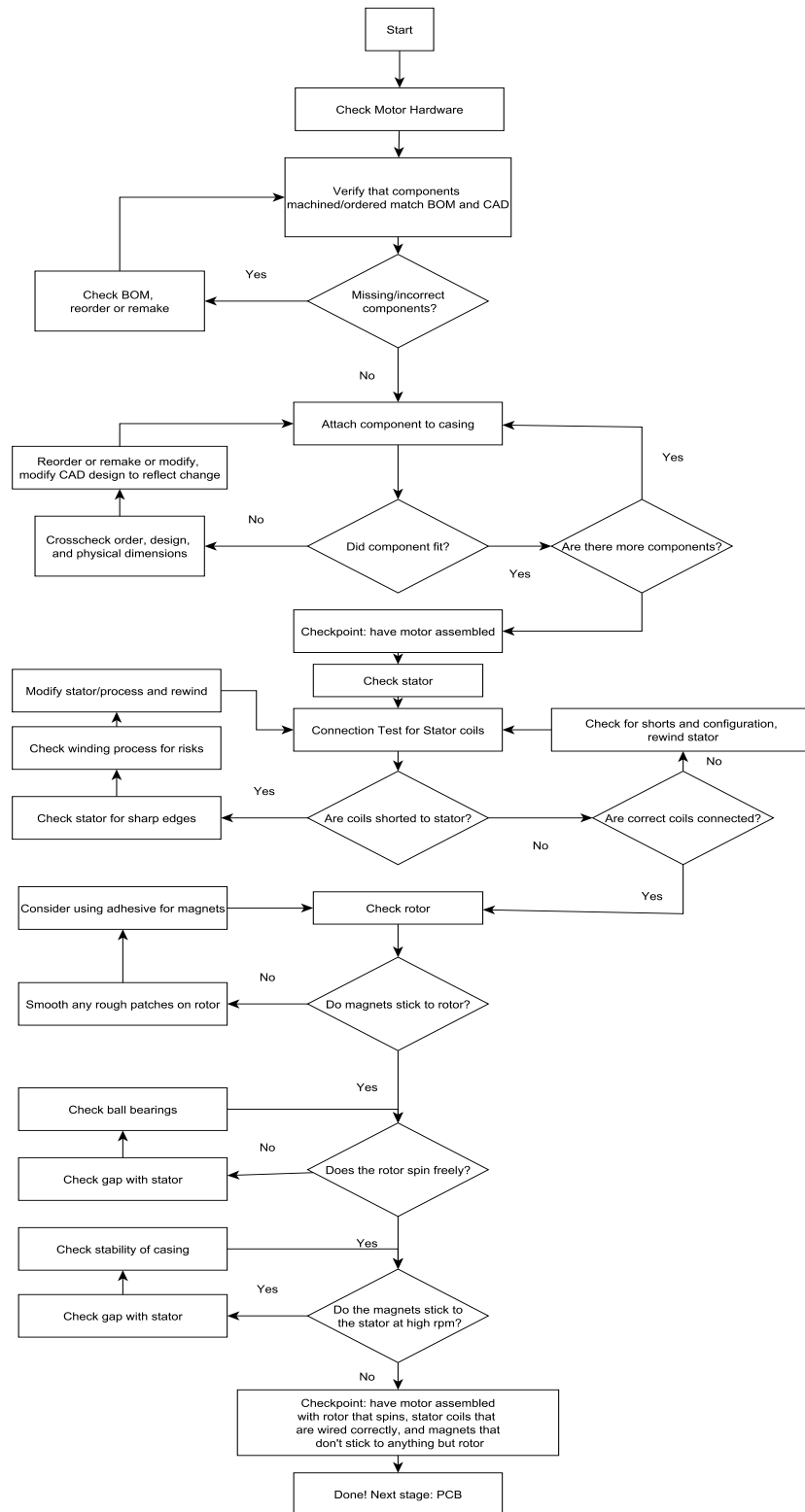


Figure 29. Mechanical Test Plan

Final Results

The Watts Our Capstone team completed the design of a motor apparatus to demonstrate concepts of electromagnetism. This system contained all of the originally proposed systems including the motor's stator, rotor, mechanical casing, main PCB for speed controller, voltage drivers, and windings around the stator. Supplemental subsystems were added to expand on desired functionality; these expansions consisted of an OLED speed display, SPI/RS232 hardware communication abilities, removable electric motor connections, and Back EMF visualization.

The displayed RPM speed calculations were verified using an optical gate sensor with speeds of 120 to 1000 RPM. The proposed functionality was constantly evaluated throughout the project's duration, and the breakdown is shown below in Tables 3 and 4. Furthermore, the extra button was written to also reverse the rotation of the motor. The overall performance was on the "A" range of the original breakdown.

Table 3. Functionality of Subsystems

	Firmware	Hardware	Mechanical
Functionality of Subsystem	<ul style="list-style-type: none">- Set the state of the driver chips with mechanical feedback from the rotor.- Deciphered change in mechanical position as angular speed in RPM.- Drove correct voltages to various windings on the motor.	<ul style="list-style-type: none">- LEDs properly displayed logic on drivers, back EMF, and Hall Effects.- OLED displayed current speed in RPM and duty cycle of PWM- Physical buttons properly increased/decreased speed and powered the motor.	<ul style="list-style-type: none">- Windings properly induced magnetic field in steel motor.- Rotor moved smoothly and securely on shaft.- Motor is safely operating, with minimal loose wires.

Table 4. Letter Grade Breakdown

	Overall A Grade	Overall B Grade	Overall C Grade	Overall D Grade
Requirements for Overall Grade	Firmware, hardware, and mechanical subsystems all work	2/3 of the subsystems work	1/3 of the subsystems works	0/3 of the subsystems work

All of the three systems above ultimately worked in unison to spin and control the motor, as shown in the video demonstration. However, in order to troubleshoot certain mechanical issues a few slight modifications were made to the design. The solved problems are outlined below:

1. *Horizontal shearing of the rotor/plexiglass on the shaft* - The stator of the motor was not perfectly round due to the laminations shifting during the waterjet cutting. This originally caused the rotor to not fit in the inner diameter of the stator. Upon closer inspection later on, it was found that the imperfect circle shape of the stator caused the shaft to not spin directly in the center. This problem was solved with the 3D printed brace placed on top of the stator to firmly lock the rotor perpendicular to the plane of the plexiglass mounts. The design of the brace is shown below in Figure 30.

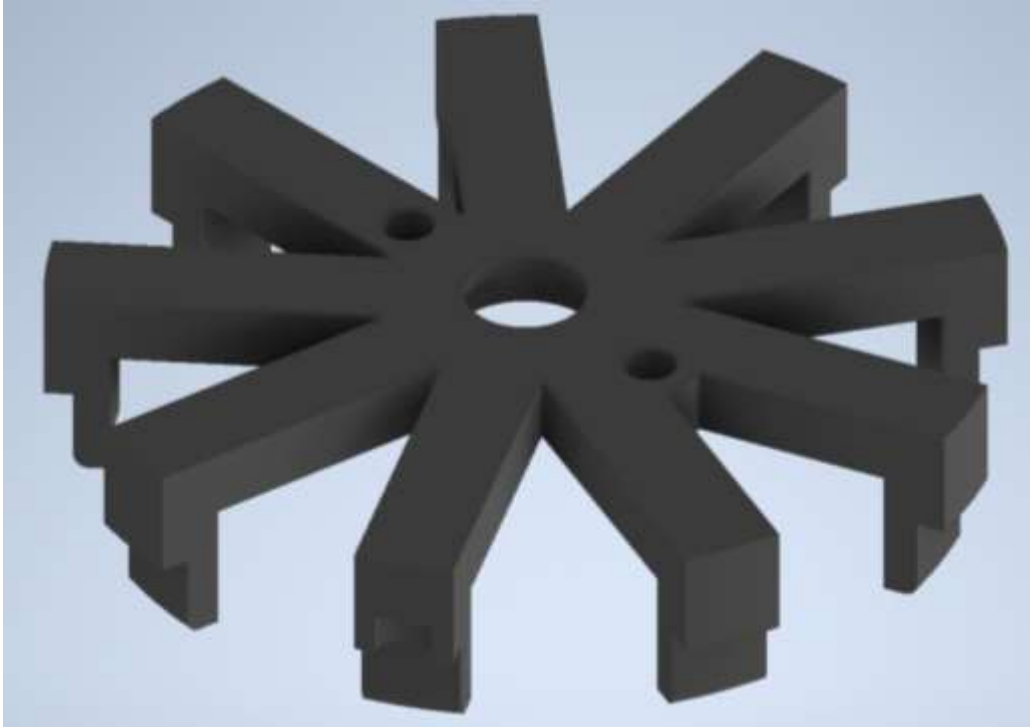


Figure 30. 3D Printed Stator Brace

2. *High cogging torque* - Once the rotor was safely spinning again, the firmware was tested in an attempt to control the spin. The constrained 24 V 1 A supply was not enough to overcome the cogging torque of the motor. Cogging torque is the interaction between the steel spokes on the stator and the permanent magnets, which causes jerkiness at low speeds and can even prevent any kind of spinning motion [50]. This was solved by reducing the number of magnets for the demonstration to 2 poles. This solution also required the firmware to be reworked in an open loop configuration. The gaps in-between the magnets created undefined states in the FSM, which could no longer be implemented in a predictable fashion for successful closed loop implementation.

Costs

The total cost of the original system produced this semester was \$472.19 This included the fabrication of two PCBs, 3D printing materials, hardware for system assembly, and magnetic motor components. A few extra parts were ordered in case of malfunction or parts breaking. The mass production of the product was estimated using a combination of McMaster-Carr, Digikey, and PCBway to quote the cost for an order of 10,000 motors. A comparison of cost-per-unit is shown below in Table 5.

Table 5. Costs for Production

Item	Cost for 1 BLDC System	Cost for 1 BLDC if 10,000 Produced
Main PCB	\$109.05	\$35.68
Hall Effect PCB	\$43.63	\$6.96
3D Printing	\$88	\$20.00
Silicon Steel	\$0	\$36.28
PlexiGlass	\$0	\$9.74
Magnets	\$66.56	\$45.48
Magnetic Wire	\$28.8	\$17.97
Assorted Hardware	\$118.84	\$98.85
Total Cost	\$454.88	\$270.96

The most expensive part of this project were the parts required for motor construction which included hardware, steel, and magnets. For the project completed in school, the Silicon steel and plexiglass were donated. But even when including these unaccounted costs for the mass production of 10,000 units, the bulk ordering of parts was more cost effective. The mass production decreased the cost-per-unit by almost 200 dollars, which is about 40% less expensive. The above table includes all of the component costs including the microcontroller, but it does not account for the anticipated sunk costs of manufacturing equipment such as an SMT pick-and place machine, stamp press, and a CNC router.

Future Work

As mentioned throughout the report, SPI and RS232 hardware communication ports were routed into the design of this system. This offers the opportunity to future students and faculty to write software defined user interfaces for the monitors in the lab. This would allow seemingly automatic communication of the driving voltages, the observed speed, back EMF, and interrupts from the buttons. Other future works include attaching a load to the motor to observe the importance of torque, which was not explored in detail in this project. Torque could be used to set the speed of the motor for a specific speed in rotations per minute (RPM) to begin with, instead of toggling the speed until the desired rate was met. This would involve harder embedded programming that took torque into account.

Various setbacks occurred with the construction of the motor, mostly relating to tolerances when constructing a moving system. These struggles included the slight expansion of the motor's steel, the steel cutting through the preliminary wire windings, and the flexing of the plexiglass. Most of these issues could be improved by using industrial processes with better tolerances. Due to this capstone team consisting of only electrical engineers, the mechanical setbacks could have been avoided with interdisciplinary advising for the system. The addition of a mechanical engineering team would also help with large scale production. For mass production, it would also be easier to order prefabricated motors for this specific design.

Another interesting expansion of this project would be the development of a "standardized" set of power equipment for instructional use. This set of tools would be designed specifically for teaching electromagnetic energy conversion concepts. Innovative tools would include a transformer made of both E-shaped and O-shaped laminations, an AC synchronous motor, and power transmission line modelling. By having similar lab equipment for each unit, students would become accustomed to the connections made and different leads on each of the devices.

Finally, alternative designs could be used on the winding configurations, lamination stacks, or even embedded code implementation. This could include delta winding configurations, different magnets, or even configuring the motor to have the rotor on the outside. The code could be reworked with the originally planned closed-loop solution, but only if another method was used for reading the mechanical position of the rotor.

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Appendix

Appendix A: Bill of Materials

Manufacturer Part Number	Manufacturer	Digi-Key Part Number	Quantity	Unit Price	Extended Price	Description	Date Ordered
MSP-EXP430F5529LP	Texas Instruments	296-36506-ND	1	15.59	\$15.59	LAUNCHPAD MSP430F5529 EVAL BRD	09/18/2020
BTN8982TAAUMA1	Infineon Technologies	BTN8982TAAUMA1INCT-N	4	5.15	\$20.60	IC MOTOR DRIVER PAR TO263-7	10/12/2020
LD1086DT33TR	STMicroelectronics	497-3446-1-ND	2	0.98	\$1.96	IC REG LINEAR 3.3V 1.5A DPAK	10/12/2020
TL331IDBVR	Texas Instruments	296-10168-1-ND	5	0.56	\$2.80	IC DIFF COMP SINGLE SOT23-5	10/12/2020
MJTP1230	APEM Inc.	679-2428-ND	5	0.1	\$0.50	SWITCH TACTILE SPST-NO 0.05A 12V	10/12/2020
DRV5013ADQDBZR	Texas Instruments	296-37538-1-ND	5	0.426	\$2.13	MAGNETIC SWITCH LATCH SOT23-3	10/12/2020
MAX3232ECDWR	Texas Instruments	296-19852-1-ND	2	1.48	\$2.96	IC TRANSCEIVER FULL 2/2 16SOIC	10/12/2020
SN74LVC1G126DCKR	Texas Instruments	296-11606-1-ND	5	0.26	\$1.30	IC BUF NON-INVERT 5.5V SC70-5	10/12/2020
SN74LVC1G125DCKR	Texas Instruments	296-11604-1-ND	5	0.26	\$1.30	IC BUF NON-INVERT 5.5V SC70-5	10/12/2020
QTLP651C4TR	Everlight Electronics Co Ltd	1080-1484-1-ND	15	0.279	\$4.18	LED GREEN CLEAR 1206 SMD	10/12/2020
CC0603ZRY5V9BB104	Yageo	311-1343-1-ND	18	0.046	\$0.82	CAP CER 0.1UF 50V Y5V 0603	10/12/2020
CR0603-FX-82R0ELF	Bourns Inc.	CR0603-FX-82R0ELFCT-N	15	0.015	\$0.22	RES SMD 82 OHM 1% 1/10W 0603	10/12/2020
A-DF 09 A/KG-T4S	Assmann WSW Components	AE10924-ND	2	0.78	\$1.56	CONN D-SUB RCPT 9POS R/A SLDR	10/12/2020
151340303	Molex	WM15255-ND	3	2.7	\$8.10	PICOBLADE 3 CIRCUIT 300MM	10/12/2020
1803581	Phoenix Contact	277-1162-ND	1	3.58	\$3.58	TERM BLOCK PLUG 3POS STR 3.81MM	10/12/2020
1803280	Phoenix Contact	277-1207-ND	1	1.26	\$1.26	TERM BLOCK HDR 3POS 90DEG 3.81MM	10/12/2020
530470310	Molex	WM1732-ND	4	0.24	\$0.96	CONN HEADER VERT 3POS 1.25MM	10/12/2020
575-8	Keystone Electronics	36-575-8-ND	3	0.85	\$2.55	CONN BANANA JACK SOLDER	10/12/2020
24SNSP.5	Remington Industries	2128-24SNSP.5-ND	1	13.87	\$13.87	24SNSP.5 MAGNET WIRE, ENAMELED C	10/12/2020
5011	Keystone Electronics	36-5011-ND	2	0.4	\$0.80	PC TEST POINT MULTIPURPOSE BLACK	10/26/2020
5010	Keystone Electronics	36-5010-ND	3	0.4	\$1.20	PC TEST POINT MULTIPURPOSE RED	10/26/2020
5012	Keystone Electronics	36-5012-ND	6	0.4	\$2.40	PC TEST POINT MULTIPURPOSE WHITE	10/26/2020
5014	Keystone Electronics	36-5014-ND	6	0.4	\$2.40	PC TEST POINT MULTI PURP YELLOW	10/26/2020
5126	Keystone Electronics	36-5126-ND	2	0.4	\$0.80	PC TEST POINT MULTIPURPOSE GREEN	10/26/2020
5013	Keystone Electronics	36-5013-ND	6	0.4	\$2.40	PC TEST POINT MULTI PURP ORANGE	10/26/2020

Figure 31. Electronic Components

Figure 31 above summarizes the electronic components ordered from Digikey, while Figure 32 below shows the parts ordered from McMaster-Carr.

Supplier	Product	Description	Quantity	Unit Price	Total Price	Date Ordered
McMaster Carr	6383K16	Bearings	3	5.82	17.46	10/14/2020
McMaster Carr	8632T133	Shaft	1	7.24	7.24	10/14/2020
McMaster Carr	92196A031	Screws (pack of 100)	1	7.01	7.01	10/14/2020
McMaster Carr	90107A005	Washers (pack of 100)	1	3.23	3.23	10/14/2020
McMaster Carr	91841A005	Nuts (pack of 100)	1	3.02	3.02	10/14/2020
McMaster Carr	93330A541	Standoffs	4		0.00	10/14/2020
McMaster Carr	91780A587	New Standoffs	4	14.22	56.88	11/18/2020
McMaster Carr	92949A352	Screws (pack of 5)	2	7.92	15.84	11/18/2020
McMaster Carr	90107A033	Washers (pack of 25)	1	8.16	8.16	11/18/2020
		Total Assorted Hardware			118.84	
McMaster Carr	7588K77	Wire	1	28.8	28.80	10/14/2020
KJ Magnetics	AX2C45-N	Magnets	4	8.32	33.28	10/14/2020
KJ Magnetics	AX2C45-S	Magnets	4	8.32	33.28	10/14/2020
KJ Magnetics	AX2C45-N	Spare Magnets	2	8.32	16.64	11/11/2020
KJ Magnetics	AX2C45-S	Spare Magnets	2	8.32	16.64	11/11/2020

Figure 32. Mechanical Components

Appendix B: Project Costs

Project costs included PCBs, parts order, and prototyping of the mechanical system. A breakdown of the cost calculations is outlined below.

Component	Quantity per Motor	Units per pack	Total units	Cost per unit	Total
Bearings	3	1	30000	5.82	174600
Shaft	1	1	10000	7.24	72400
Standoffs	4	1	40000	14.22	568800
Screws	8	5	16000	7.92	126720
Washers	8	25	3200	8.16	26112
Screws 2	15	100	1500	7.01	10515
Washers 2	15	100	1500	3.23	4845
Nuts	15	100	1500	3.01	4515
Total					988507
Cost per unit	98.8507				

Figure 33. Mass Production Hardware Cost Calculations

Figure 33 above shows how the hardware mass production costs were calculated using quotes from McMaster-Carr. Additional ongoing budget tracking was done throughout the semester to ensure the project remained under the 500-dollar limit. This is shown below in Figure 34.

Order	Description	Cost	Total Budget Remaining
-	-	-	\$500.00
Order 9/18	MSP-EXP430F5529LP	\$15.59	\$484.41
Order 10/10	PCB #1	\$33.00	\$451.41
Order 10/12	Digikey Order #1	\$56.76	\$394.65
Order 10/14	Magnets and McMasterCarr	\$141.68	\$252.97
Order 10/26	Digikey Order #2	\$10.00	\$242.97
Order 11/6	PCB #2	\$33.00	\$209.97
Order 11/11	Extra Magnets	\$33.28	\$176.69
Order 11/12	3D Printing	\$68.00	\$108.69
Order 11/18	McMaster Carr	\$80.88	\$27.81

Figure 34. Budget Tracking Calculations

As explained in the project cost section of this report, the comparison for mass production was evaluated on the metric of cost-per-unit produced. The summary of the table is shown below in Figure 35.

Item	Cost for 1 BLDC System	Cost for 1 BLDC if 10,000 Produced
Main PCB	109.05	35.68
Hall Effect PCB	43.63	6.96
3D Printing	88	20
Silicon Steel	0	36.28
Plexi Glass	0	9.74
Magnets	66.56	45.48
Magnetic Wire	28.8	17.97
Assorted Hardware	118.84	98.85
Total Cost	454.88	270.96

Figure 35. Cost Comparison for 10,000 Units